A Unified Description of Intraseasonal, Interannual and Epochal Changes in the Indian Summer Monsoon Rainfall: Implication for Predictability

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Intraseasonal Variability of Indian Monsoon Rainfall

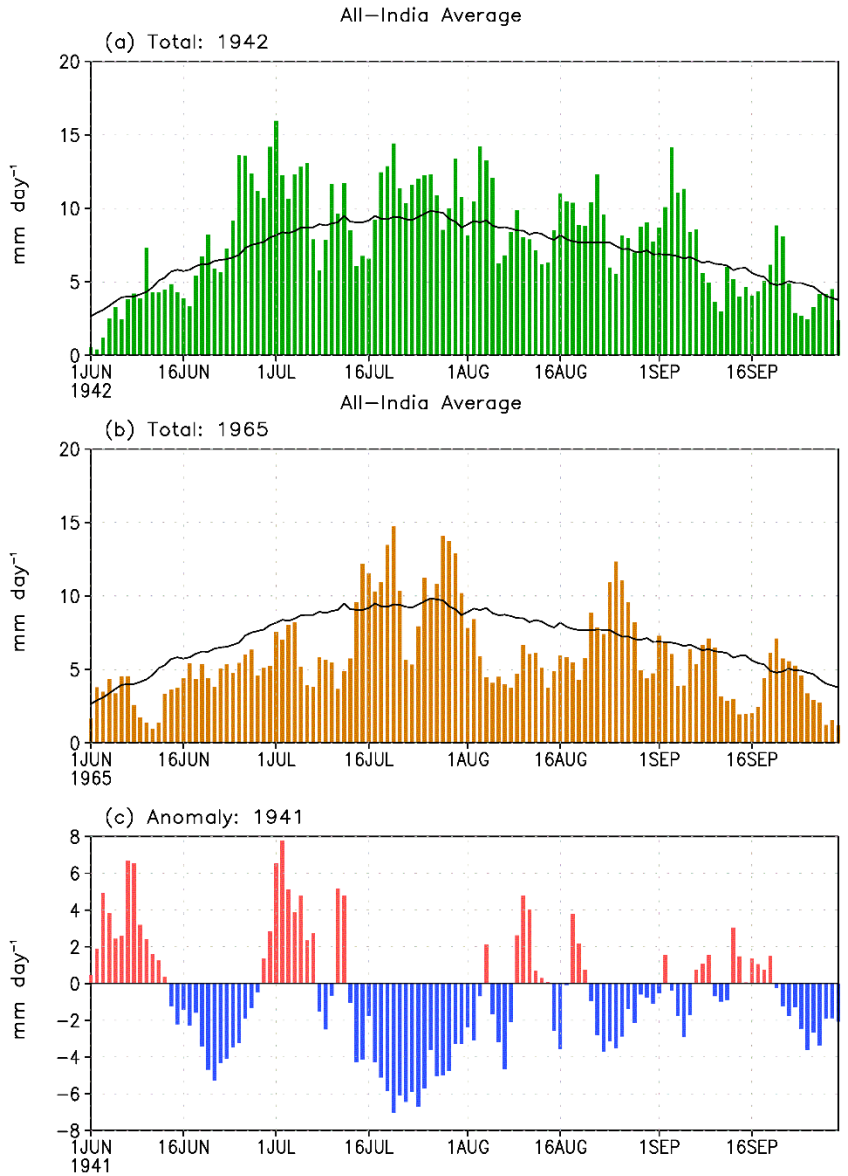
Indian summer monsoon rainfall

All-India Monsoon (AIM) index:
Area average over land points of India

1942 Daily mean and Climatology
Above-normal seasonal rainfall

1965 Daily mean and Climatology
Below-normal seasonal rainfall

1941 Daily anomaly
Active and break phases
Indication of oscillation



Interannual Variability of Indian Summer Monsoon Rainfall (1901-2021)

AIM: JJAS seasonal rainfall anomaly over land

El Nino/La Nina years:

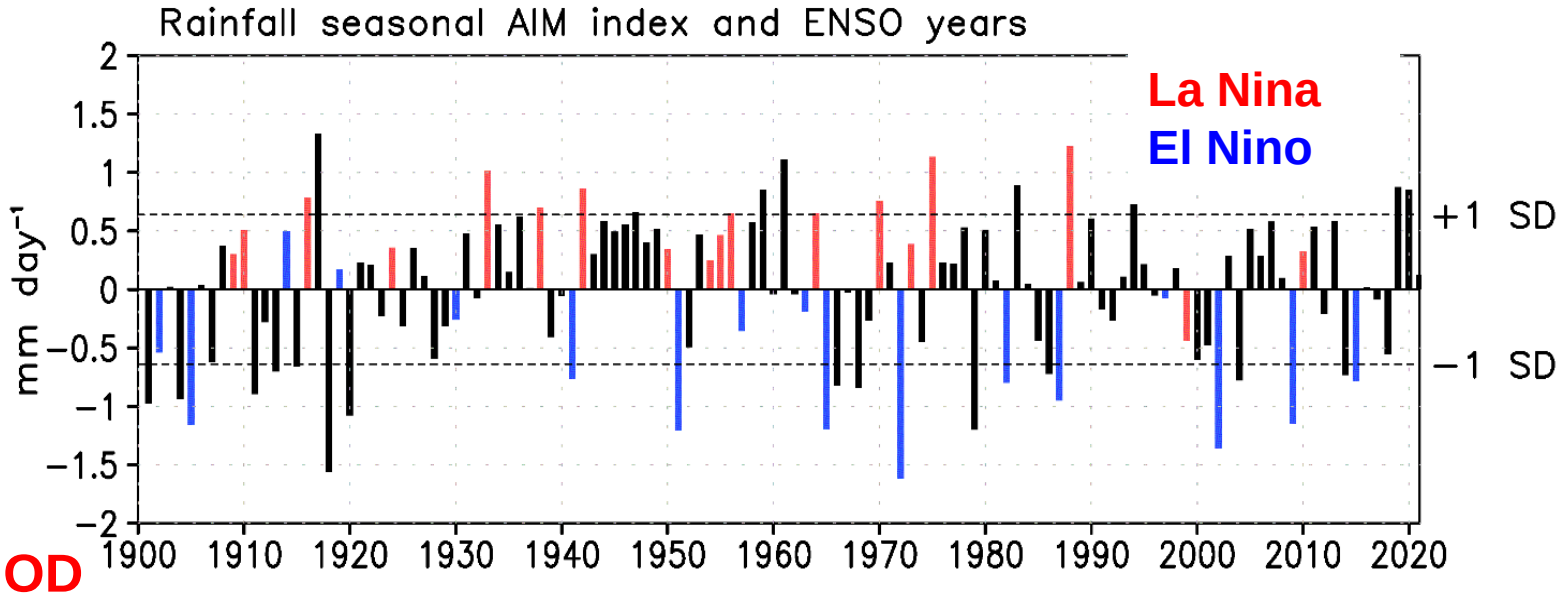
+/- 1 std. deviation of Nino 3.4: (170°W–120°W, 5°S–5°N)

Positive/Negative IOD:

+/- 1 std. deviation of IOD:

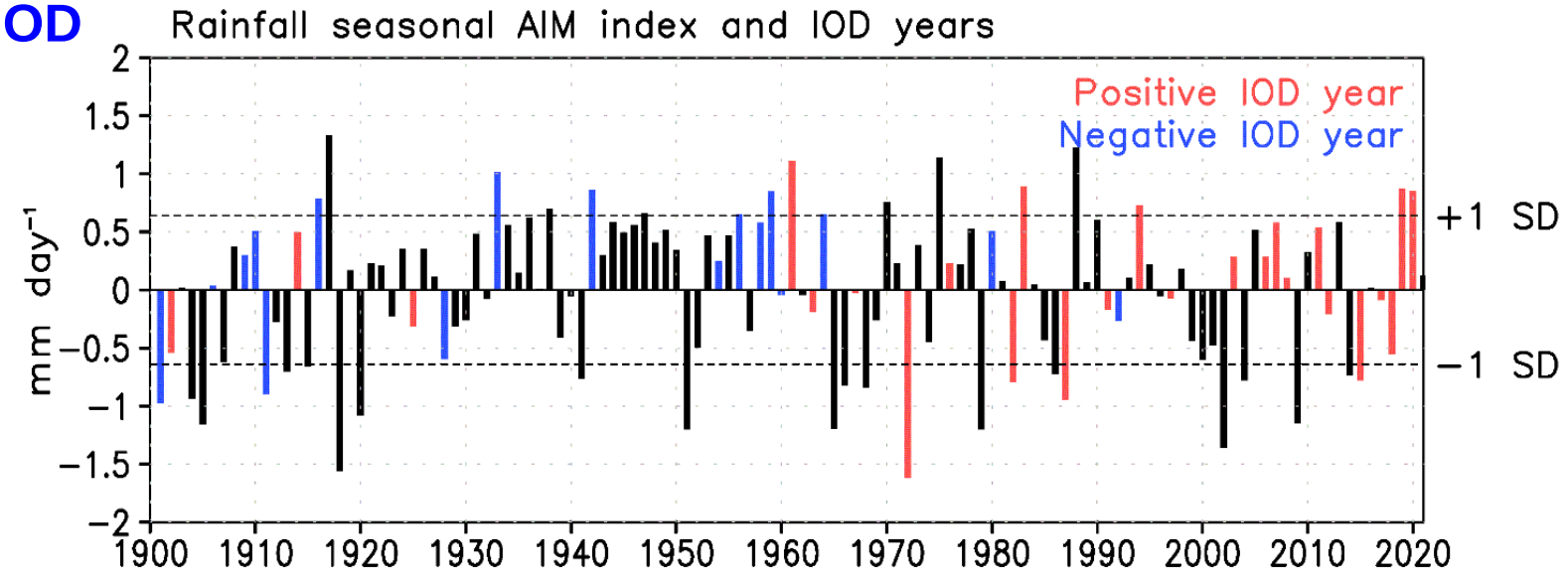
IOD = (50E–70E, 10S–10N) minus (90E–110E, 10S–EQ)

La Nina and Positive IOD give high rainfall over India



+ve IOD

-ve IOD



Outline

The first six dominant modes of multi-channel spectral analysis of unfiltered IMD gridded daily rainfall over India gives a unified description of intraseasonal variability (active/break cycles), inter annual variability related to ENSO and IOD and epochal changes in ISMR (India Summer Monsoon Rainfall)

- **Intraseasonal variability – Active-break cycle**
- **Interannual variability – Relation with Indian and Pacific oceans**
- **Epochal change in the rainfall – Relation with warming of oceans**
- **Implication for predictability**

Krishnamurthy, V., and J. Shukla, 2024: A new paradigm for active-break cycle in the Indian summer monsoon. *J. Climate*, 37, 4867-4884.

Krishnamurthy, V., and J. Shukla, 2025: Epochal change in the Indian monsoon rainfall related to warming of oceans (under review).

MSSA

MSSA (Multichannel Singular Spectrum Analysis) is "Principal Component Analysis of the covariance of time-series that is lagged successively by some interval. The dominant principal component (PC) represents the largest fraction of the correlated signal. In this paper 60 daily lags are used.

An oscillatory mode is characterized by a pair of nearly equal Singular Spectrum Analysis (SSA) eigenvalues, and associated PCs that are in approximate phase quadrature.
MSSA can find non-linear oscillations (Ghil et al., 2002)

Multichannel Singular Spectrum Analysis

The modes of monsoon variability at intraseasonal, interannual and longer time scale are obtained by using Multi-channel singular spectrum analysis (MSSA)

MSSA (also known as extended EOF) extracts space-time patterns – Particular spatial patterns with particular time patterns
Extracts time patterns such as trends, nonlinear oscillations, persistent modes

1. Start with data $X_l(t)$, at $l=1, \ldots, L$ grid points (channels) and $t=1, \ldots, N$ equally spaced in time

2. Make M lagged copies of the data and
   Construct lagged data matrix $\boldsymbol{Y}$, with dimension $M \times N'$, where $N' = N - M + 1$

3. Compute the grand lagged-covariance matrix $\mathbf{C} = (1/N')\, \boldsymbol{Y}^T\boldsymbol{Y}$, $LM \times LM$ matrix

4. Diagonalize $\mathbf{C}$ and obtain

   Eigenvectors $\boldsymbol{E}_k = \{E_k l(j)\}$, $k=1, \ldots, LM;$ $j=1, \ldots, M$ Space-time EOFs

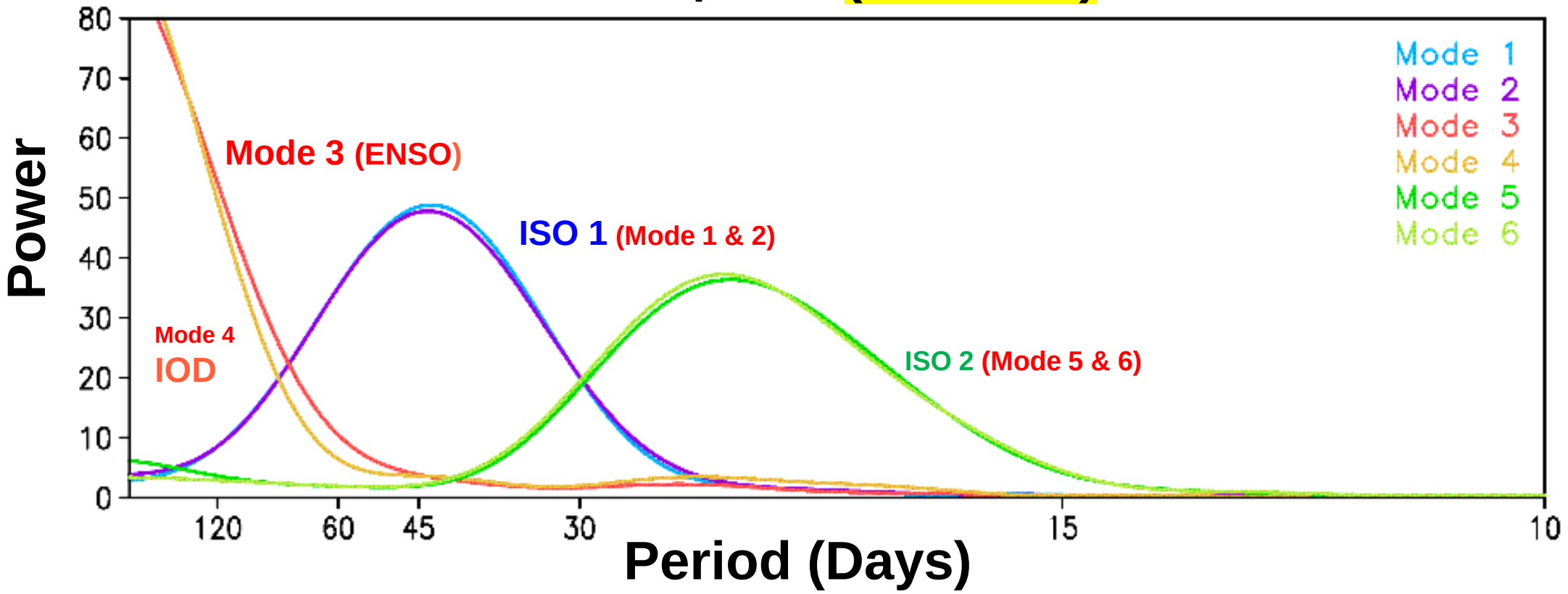
   PCs $A_k(t) = \sum_j \sum_l X_l(t+j-1)\, E_{kl}(t)$, $t=1, \ldots, N'$ Space-time PCs

   RCs (Reconstructed Components) $\boldsymbol{R_{kl}(t) = (1/M)\ \sum_j A_k(t-j+1)\ E_{kl}(j)}$

   RCs have the same spatial extent and time length as the original data.
   The sum of all the RCs is equal to the original data.

Monsoon Rainfall Modes (Daily gridded IMD, 1901-2021: .25° × .25°)

IMD Rainfall *(standardized)* Spectra (6 Modes)



MSSA: Daily rainfall anomalies from 121 years mean. **60-day lag window at one-day interval**

Six leading modes: Mode 1 and 2 (ISO1, 45 days); Mode 3 & 4: Seasonally persisting ENSO and IOD; Mode 5 & 6 (ISO2, 28 days): ISO1 and 2 are nonlinear oscillations with broad-band spectra

Intraseasonal Oscillations

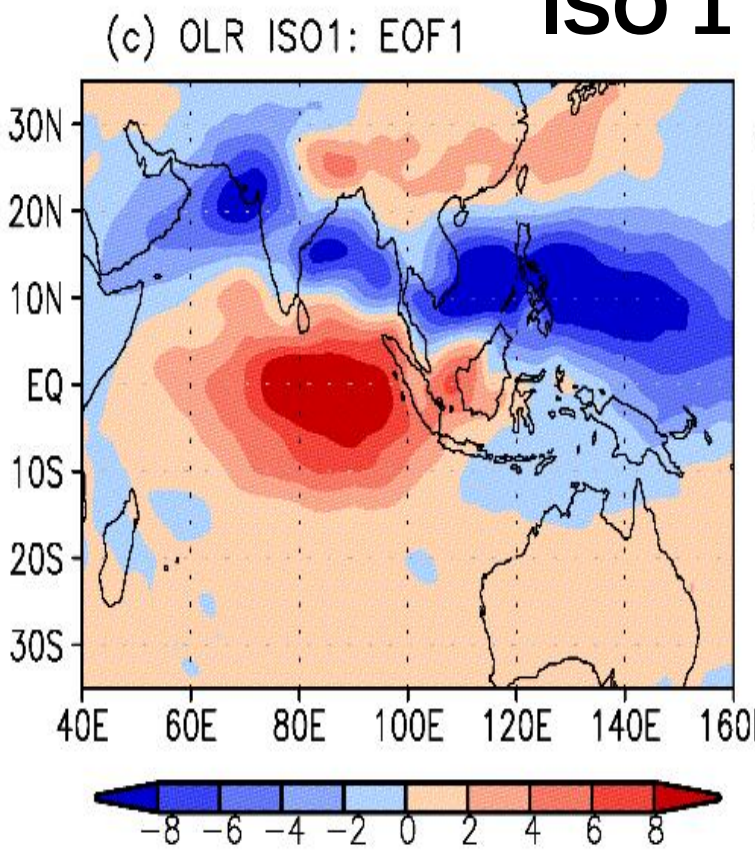
ISO1 and ISO2 in

OLR

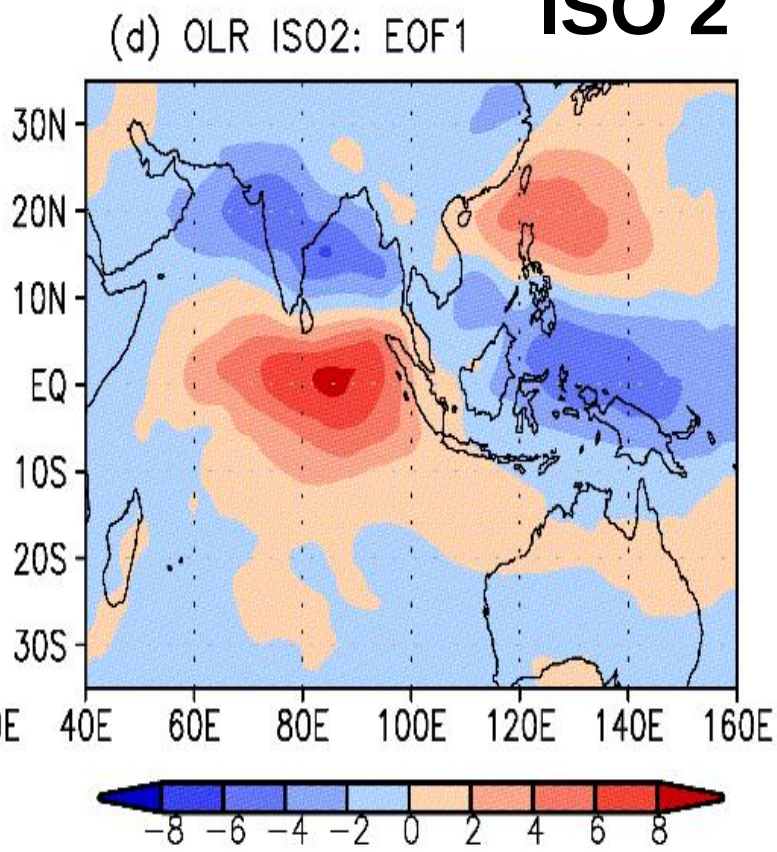
EOF of ISO1 and ISO2 obtained from MSSA

OLR: Daily JJAS 1979-2021

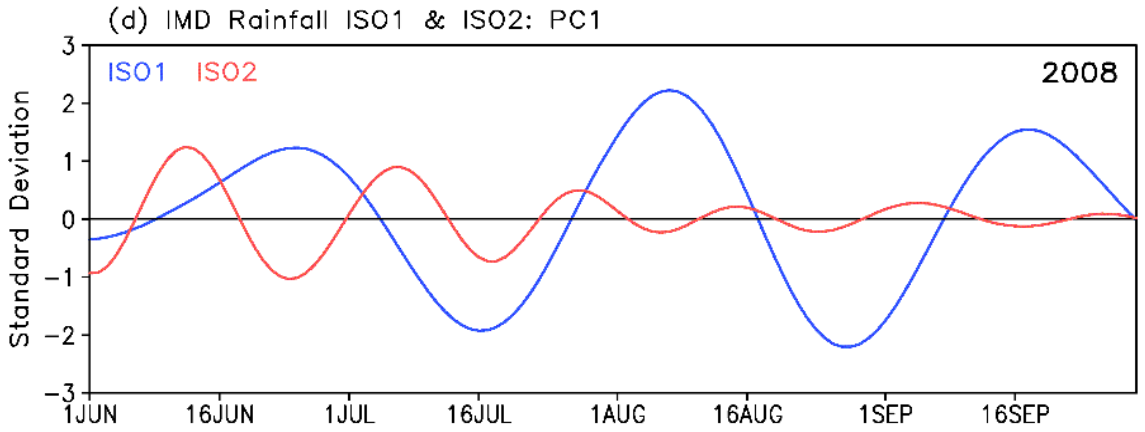
ISO 1



ISO 2



ISO1 **ISO2**



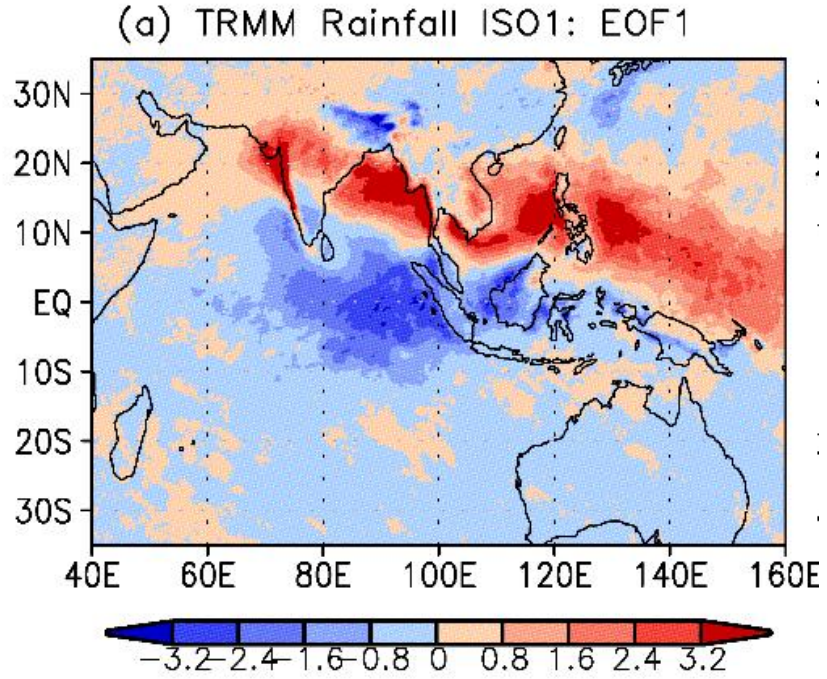
Intraseasonal Oscillations

ISO1 and ISO2 in
TRMM rainfall
OLR

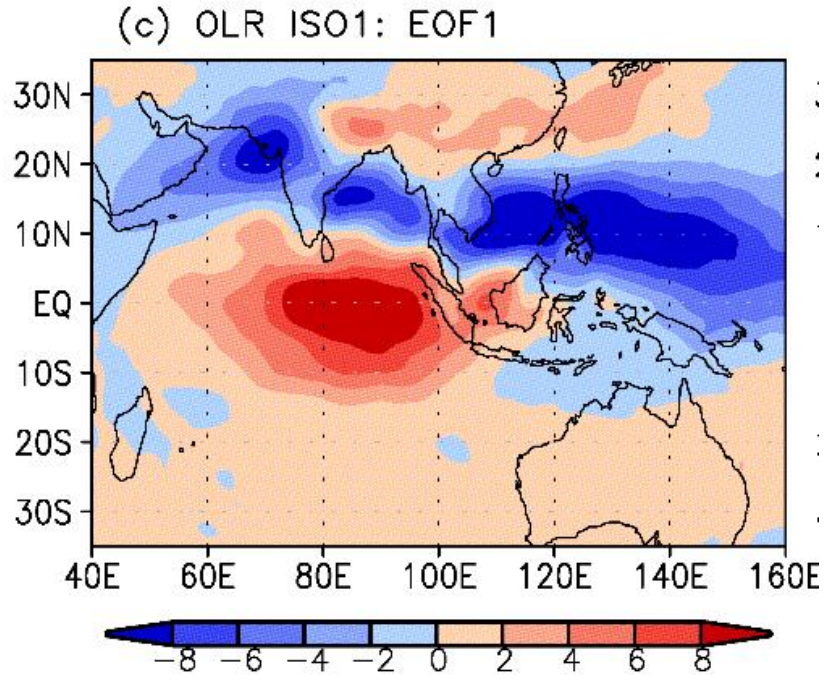
EOF of ISO1 and ISO2 obtained from MSSA

TRMM Rainfall: Daily JJAS 1998-2019

OLR: Daily JJAS 1979-2021



ISO 1
TRMM Rainfall



ISO 1
OLR

Intraseasonal Oscillation ISO1 in Rainfall and OLR

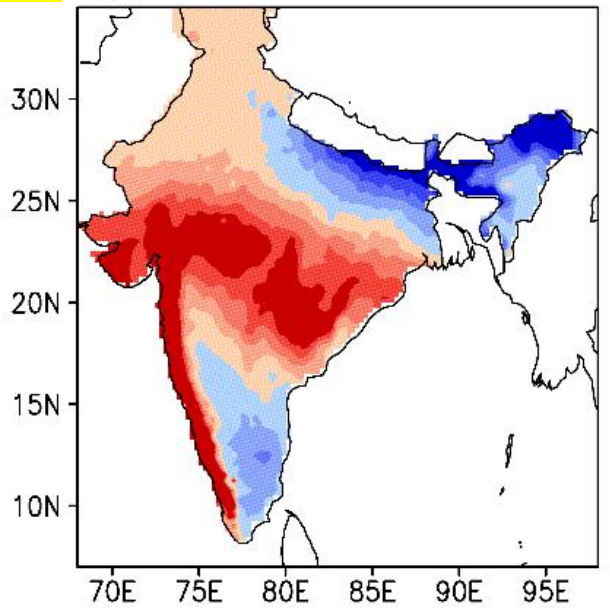
ISO1 and ISO2

EOF of ISO1 and ISO2
ISO1 (45-day period)
ISO2 (28-day period)

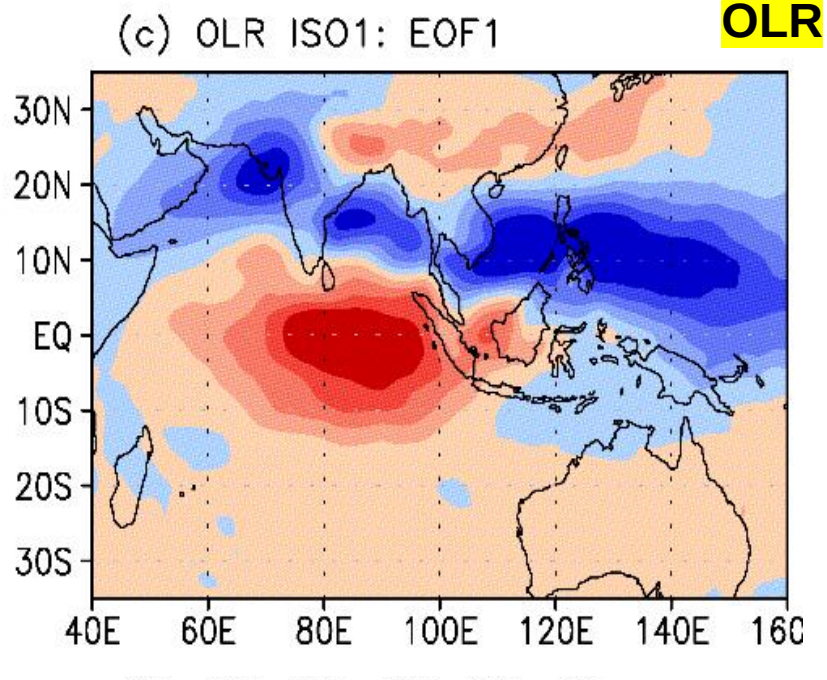
Note: Structure of ISO 1 and ISO 2 are similar but the amplitude and frequency of PCs is quite different

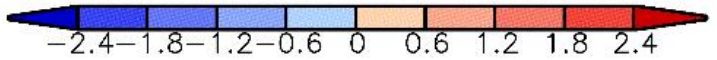
PC of ISO1 and ISO2
ISO1 and ISO2
for JJAS 2008

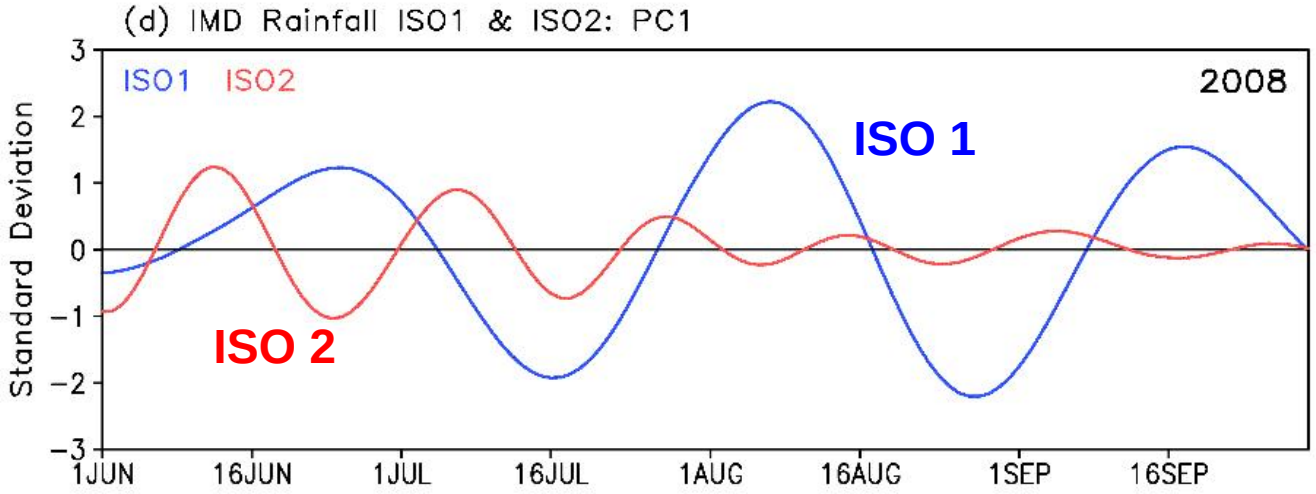
Rainfall



OLR







Propagation of ISO1

Phase composites of ISO1

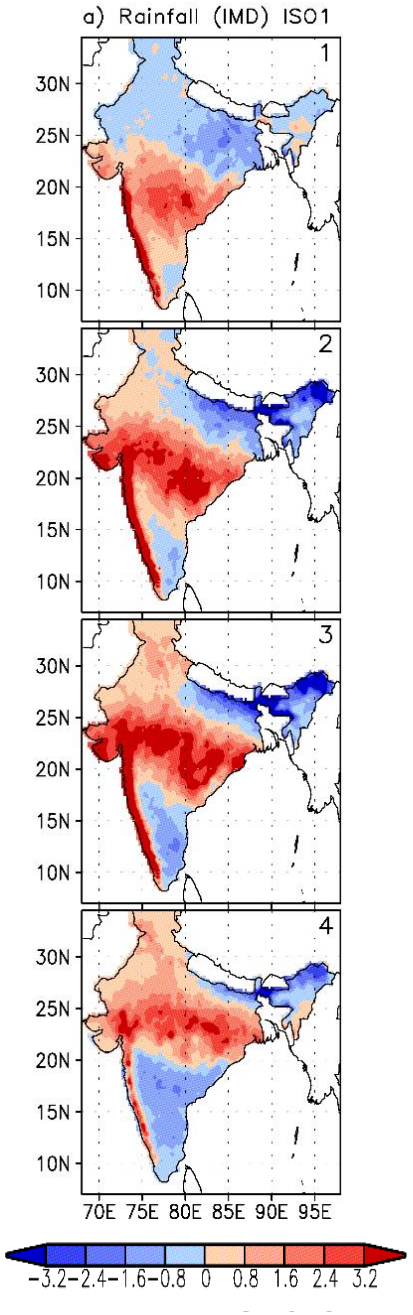
IMD rainfall
TRMM rainfall

First half cycle
In four phase intervals

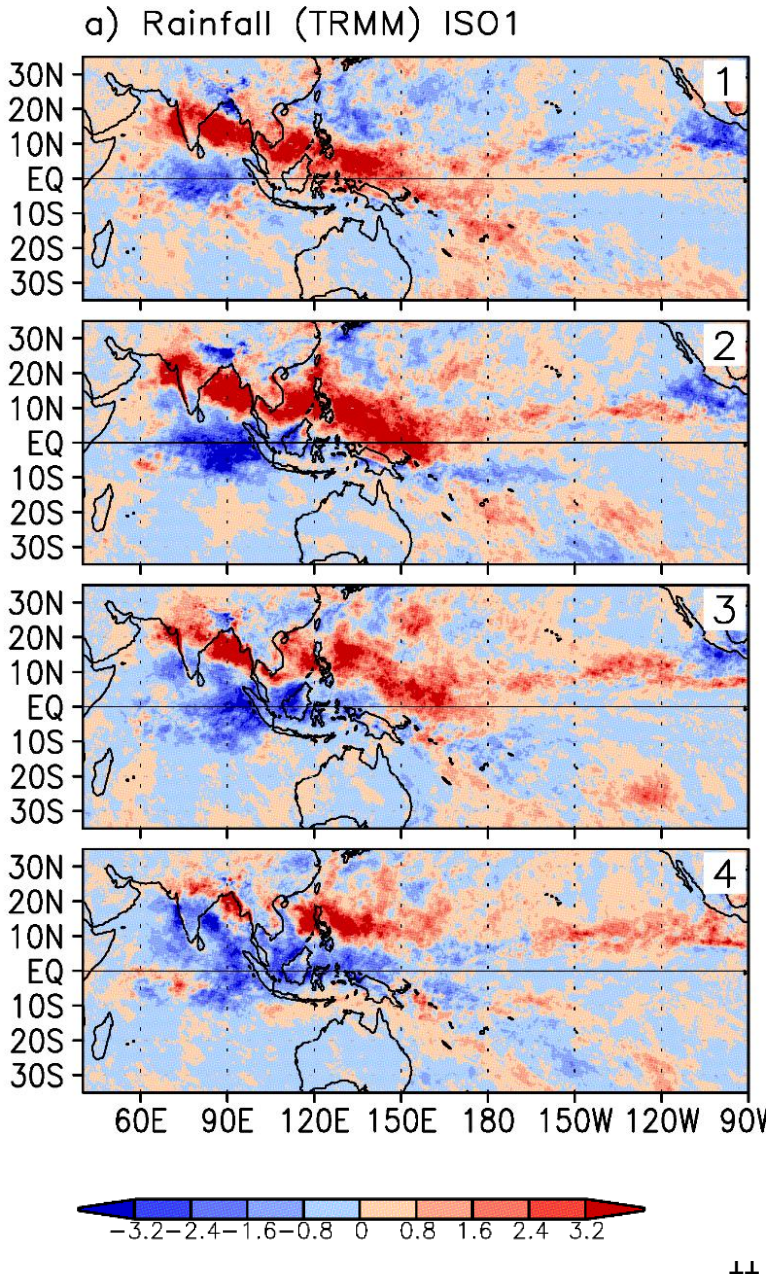
Second half cycle
(not shown) is identical
to the first half cycle
but with anomalies
of opposite sign

Northeastward Propagation

IMD



TRMM



A New Definition of Active and Break Phases

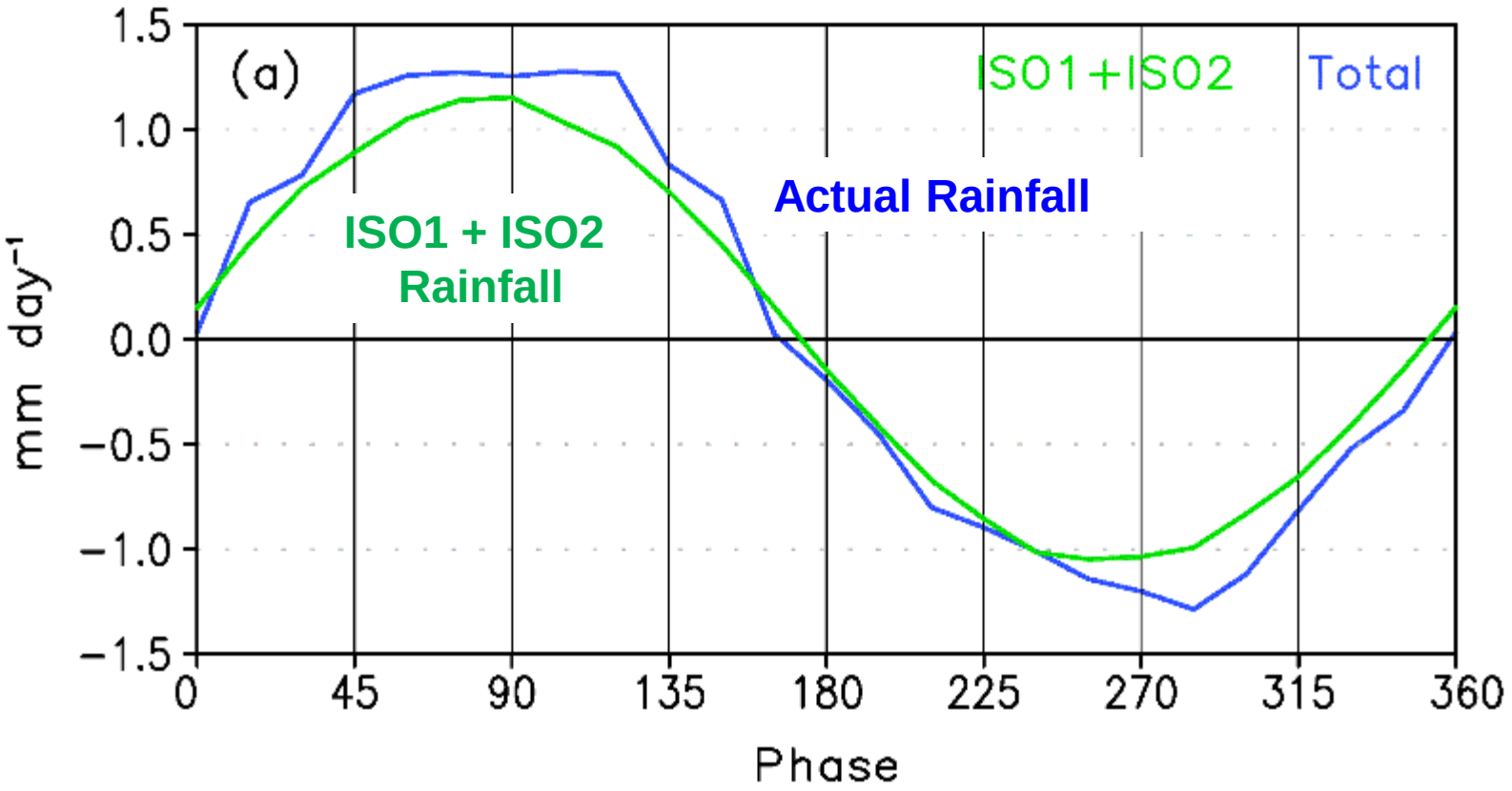
Active and Break Phases

A new definition of active and break cycles is introduced based on the phases of ISO1+ISO2

Active Period:
Phase of the AIM index is between $\pi/4$ and $3\pi/4$ (45°–135°)

Break Period:
Phase of the AIM index is between $5\pi/4$ and $7\pi/4$ (225°–315°)

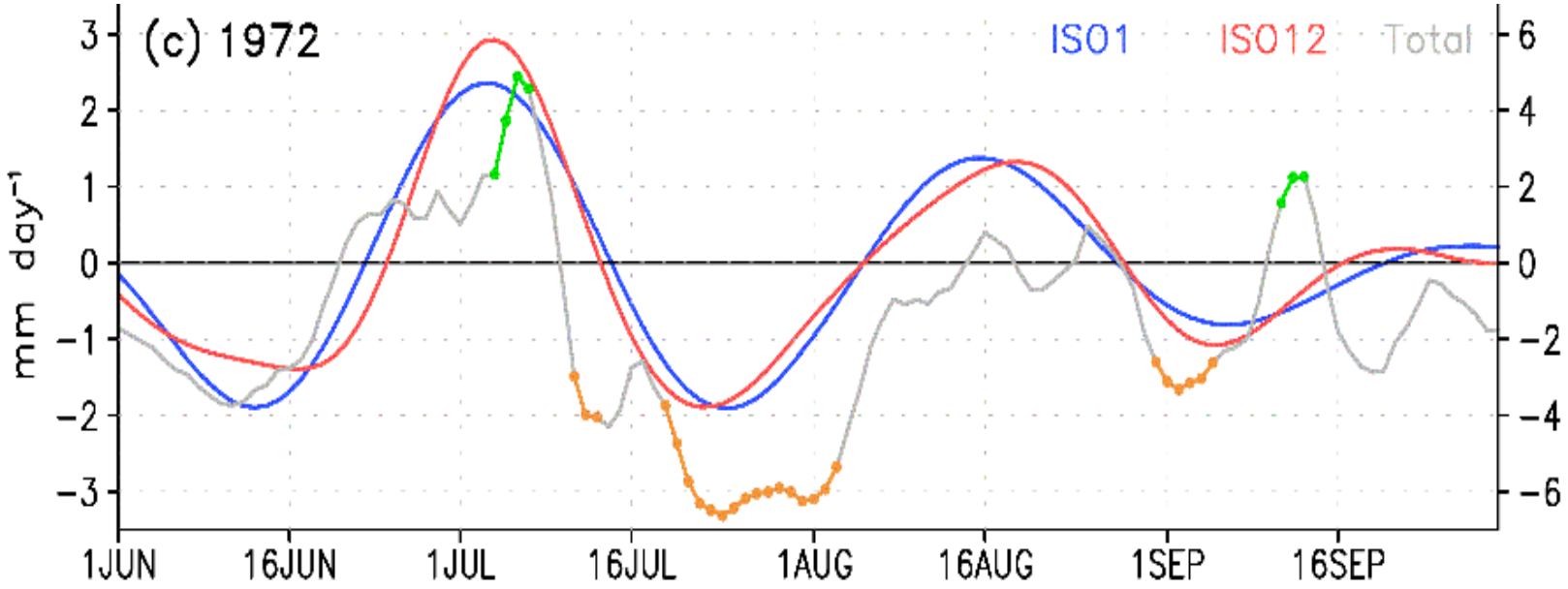
Active-break cycle of the total rainfall has close correspondence with ISO1+ISO2



Active-Break Cycle

AIM Index of ISO1 + ISO2: **Red**
AIM Index of total Rainfall: **Gray**
IMD defined active/break: **Green/Orange**

ISO1 + ISO2 well represent total rainfall anomalies



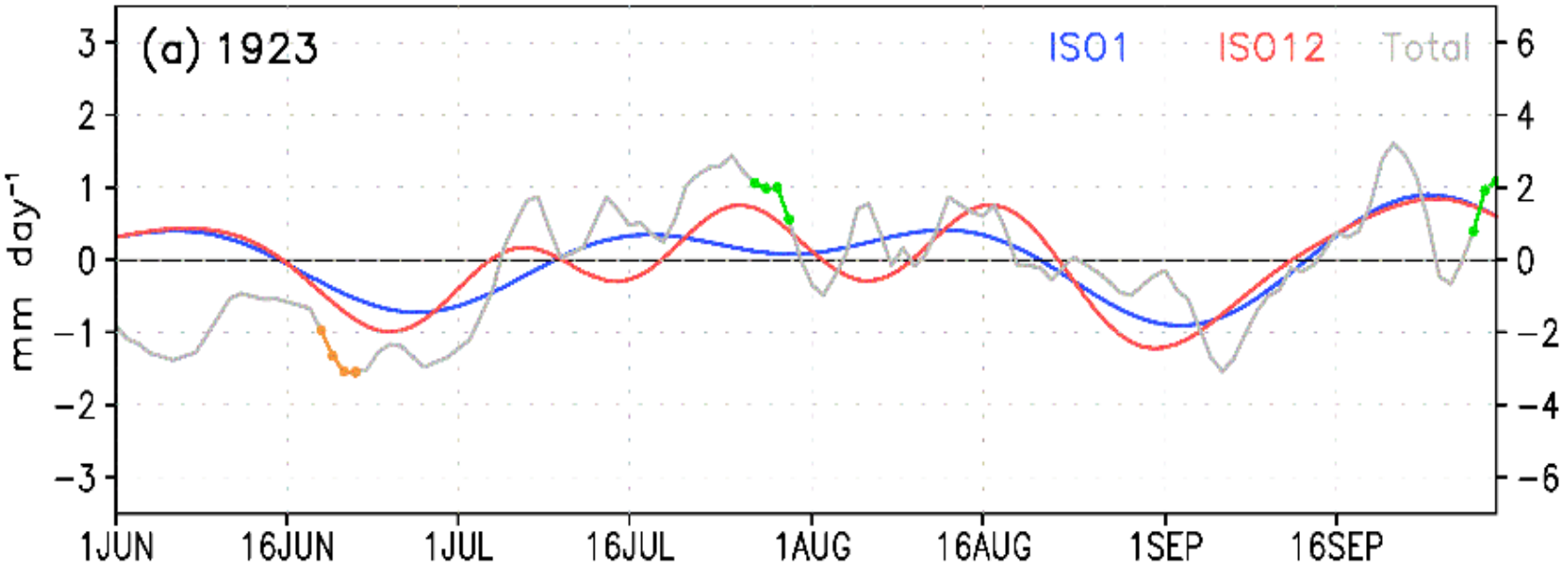
Active-break cycle of rainfall

AIM index of total rainfall anomaly (grey)
AIM index of ISO1 of rainfall (blue)
AIM index of ISO1+ISO2 of rainfall (red)

IMD-defined active-break periods (green)

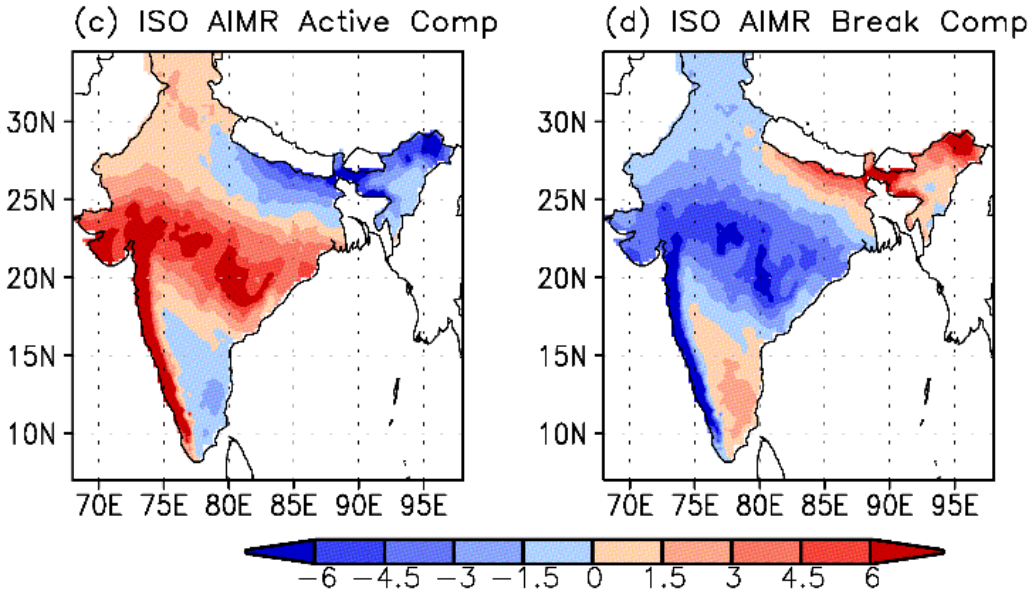
JJAS 1923, 1955, 1972, 2004

The active-break cycle of the rainfall is explained by
ISO1+ISO2 (ISO12, red)

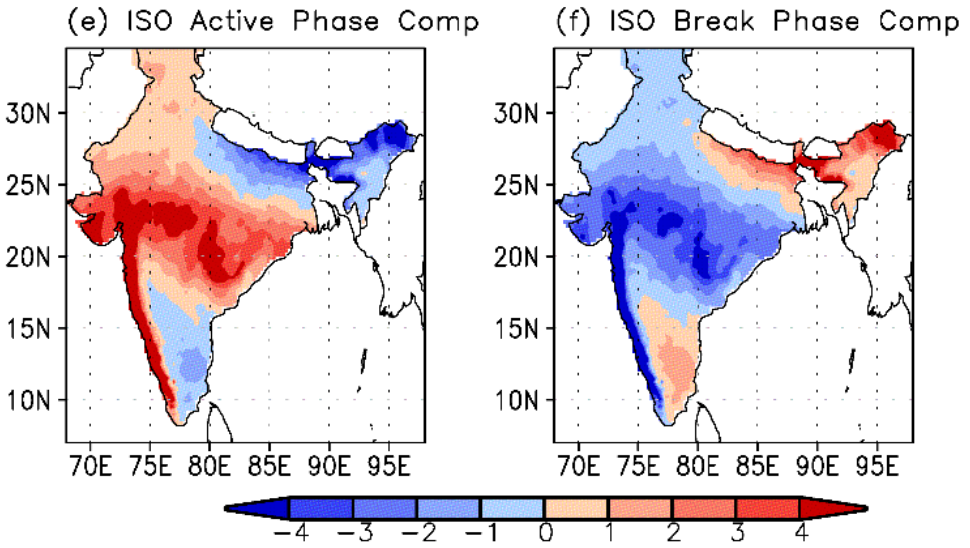


Composites of Rainfall for active and break periods (1901-2021)

Based on one standard deviation of AIM index

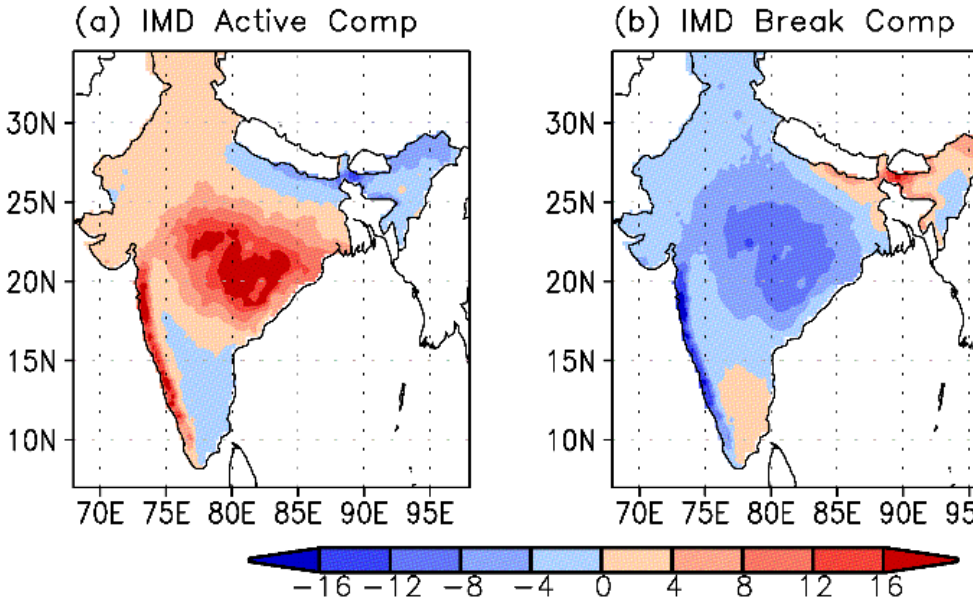


Based on active and break phases of ISO1+ISO2



Based on IMD definition

IMD definition makes the rainfall pattern localized

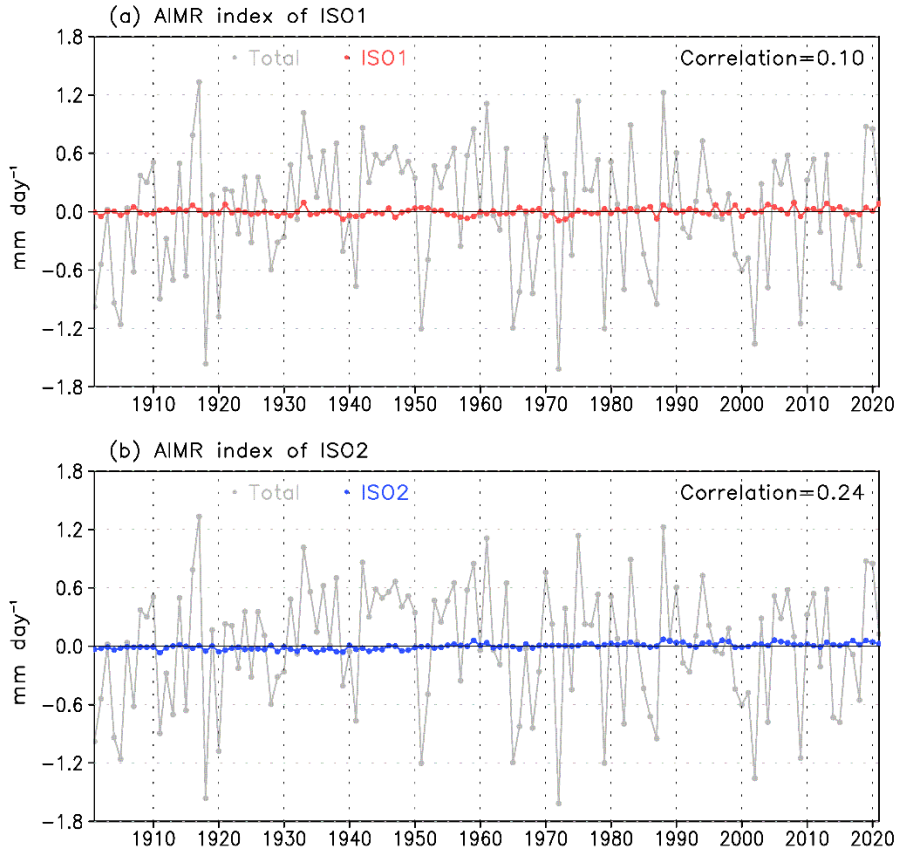


Active: 45° - 135 °
Break: 225 ° - 315°
Of combined ISO1 and ISO2

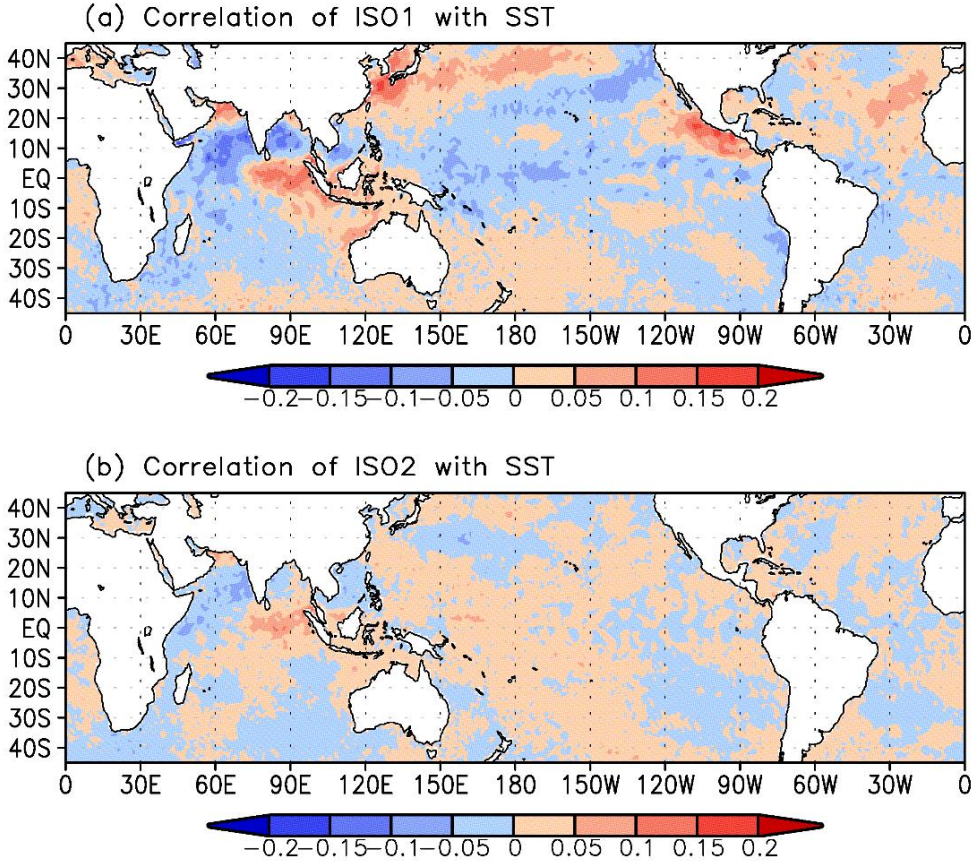
ISOs and Seasonal Mean Rainfall

ISO1 and ISO2 make negligible contribution to the seasonal mean rainfall.
The correlation of ISO1 and ISO2 with SST shows no strong relation with either Indian Ocean or Pacific Ocean

Seasonal Mean of ISO1 (Red) & ISO2 (Blue) are nearly zero



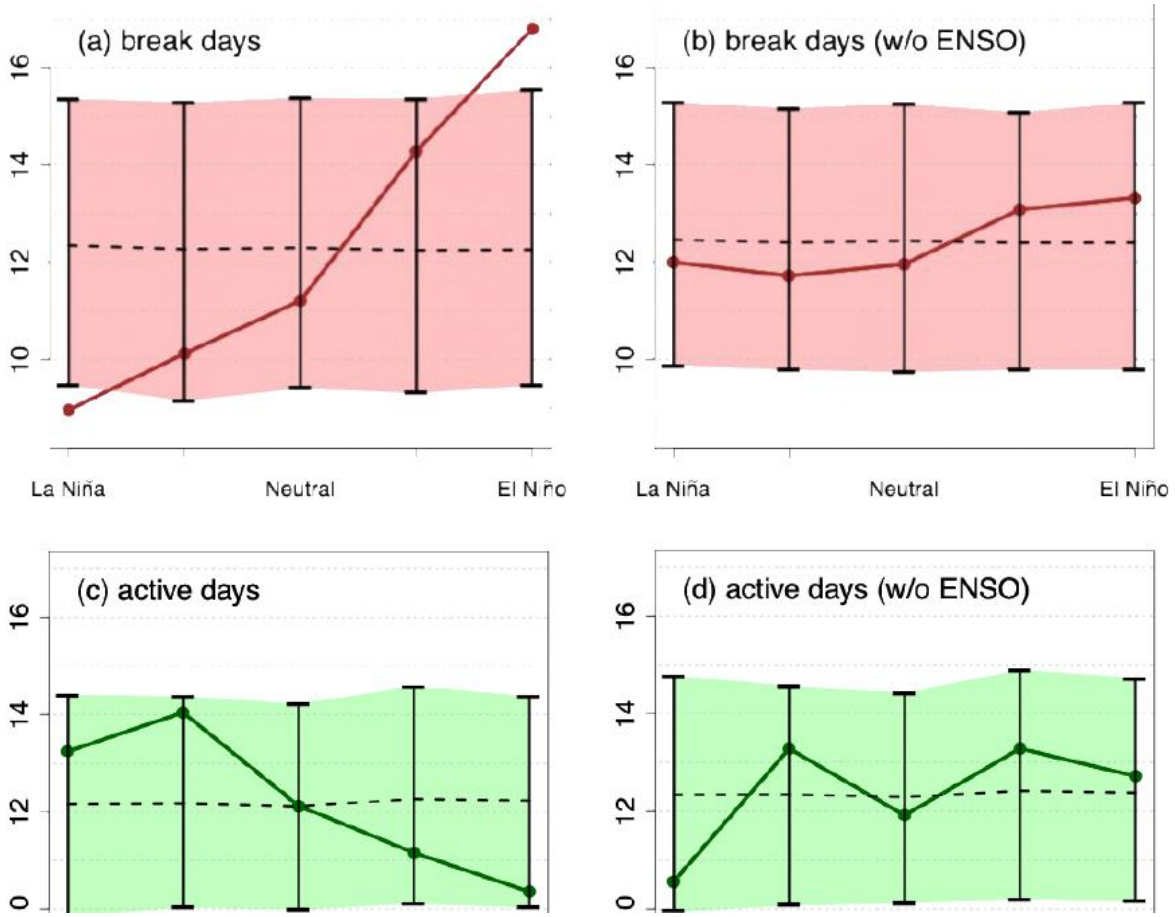
Correlation of ISO1 and ISO2 with SST are negligible



Average Active & Break day Count (JJAS)

If seasonal mean rainfall is removed, there is no difference in the active and break day counts during El Nino and La Nina

Remove 121 Year Climatology | **Remove JJAS Mean for each Pentile**



Bootstrapping (1,000 times), 90% confidence

(Monsoon Core Zone Average)

Erik Swenson &
Debanjana Das. 2025

ISO1 and ISO2 Summary

- **ISOs provide an objective definition of active and break phases without arbitrarily chosen thresholds**
- **ISOs are not influenced by ENSO or IOD or other SST effects**
- **IOSs do not contribute to seasonal mean rainfall**
- **Number of active and break days does not change in drought and flood years if seasonal mean is removed before counting the days**
- **ISOs appear to be the modes of internal dynamics of the system**

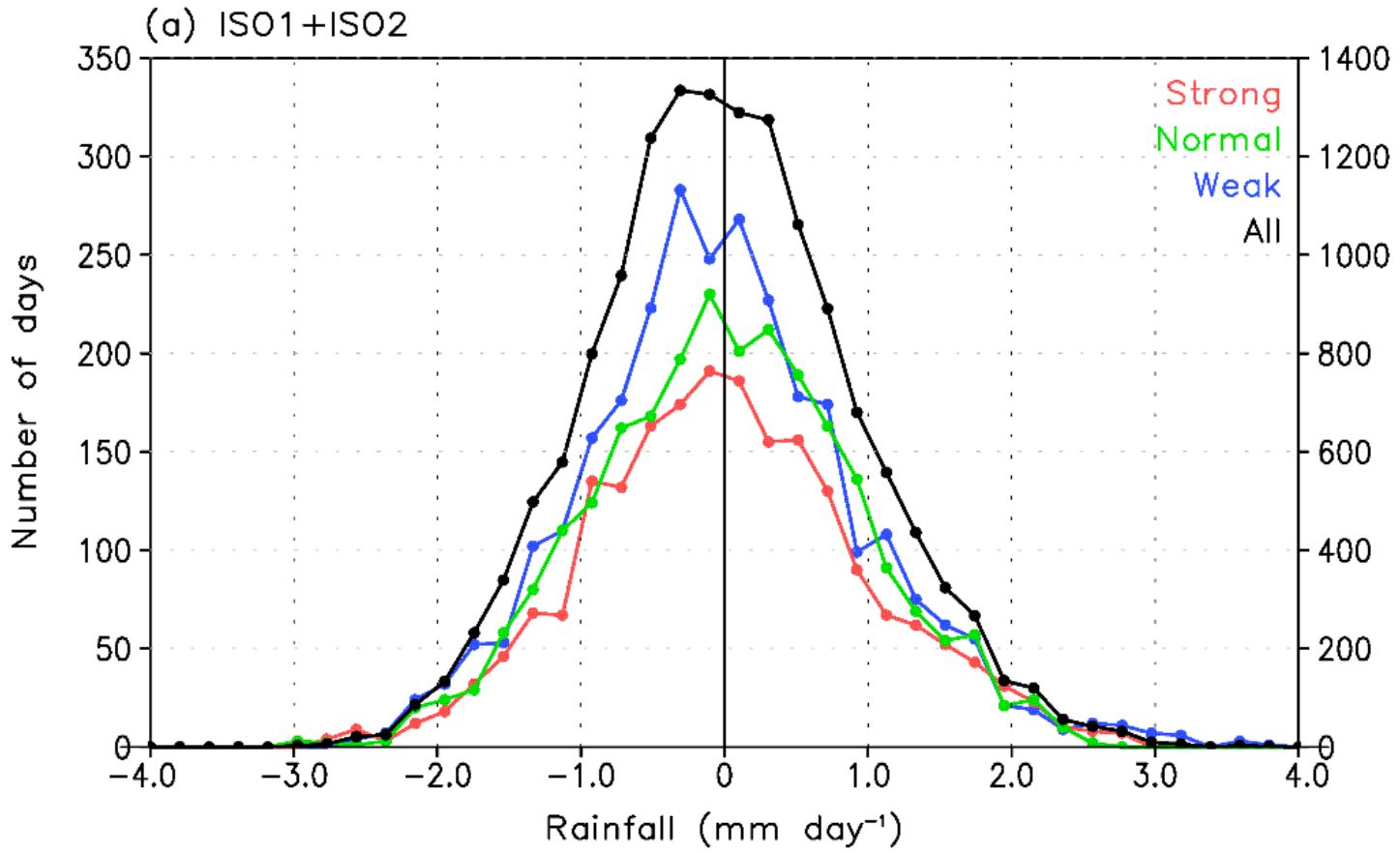
Frequency Distribution of ISOs

Lack of bimodality in frequency distribution

Frequency distribution of AIM index of ISO1+ISO2

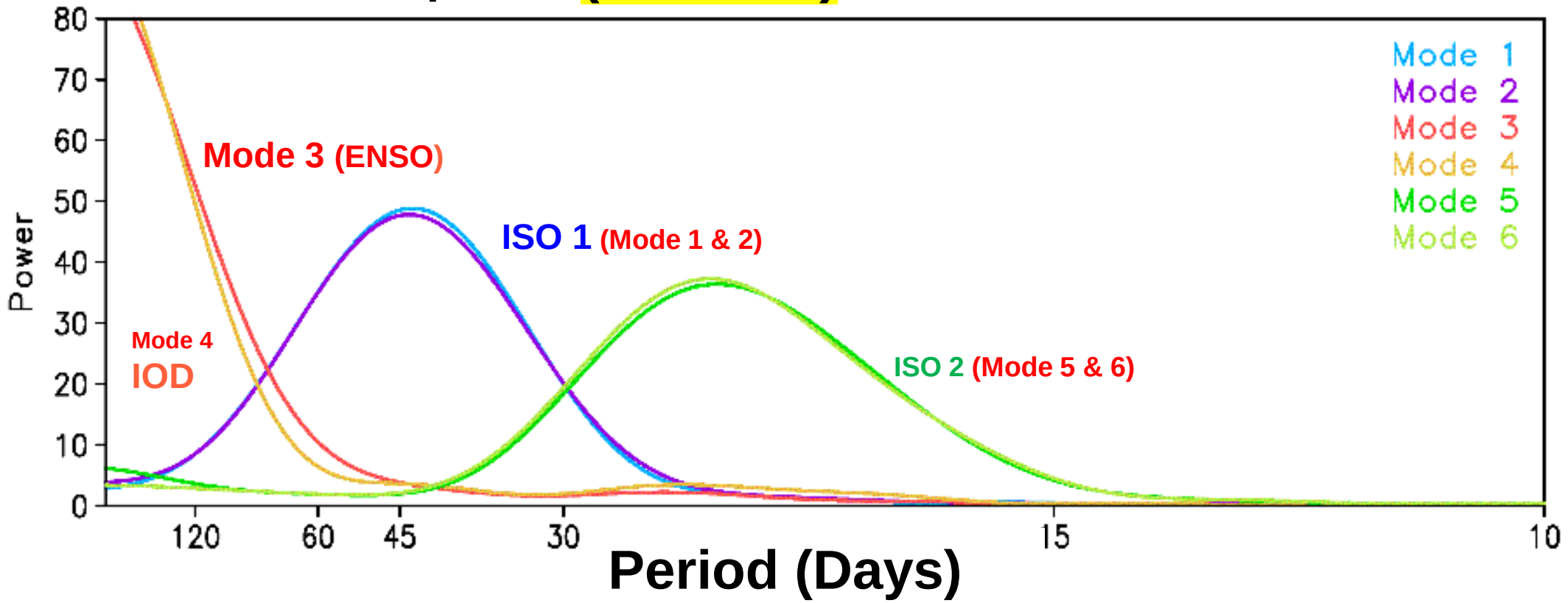
Does not show any preference for strong or weak monsoon years

Strong > 1 SD
Normal: +/- 0.25 SD
Weak < -1 SD
All



Monsoon Rainfall Modes (Daily gridded IMD, 1901-2021: .25° × .25°)

IMD Rainfall Spectra (6 Modes)



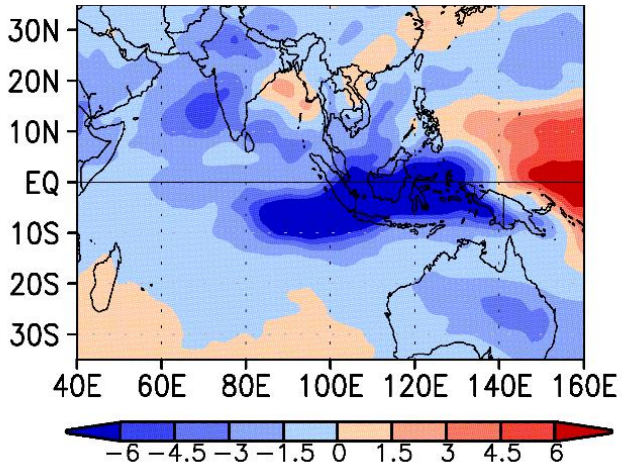
MSSA: Daily rainfall anomalies from 121 years mean. **60-day lag window at one-day interval**

Six leading modes: Mode 1 and 2 (ISO1, 45 days); Mode 3 & 4: Seasonally persisting ENSO and IOD; Mode 5 & 6 (ISO2, 28 days): ISO1 and 2 are nonlinear oscillations with broad-band spectra

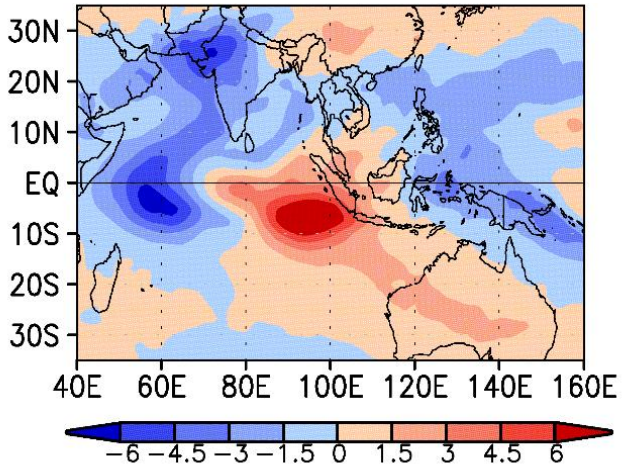
Seasonally Persisting Modes in MSSA of OLR

EOF1 of Mode 3: Monsoon-ENSO (M-ENSO): Seasonally Persisting Mode
EOF1 of Mode 4: Monsoon-IOD (M-IOD) Mode: Seasonally Persisting Mode

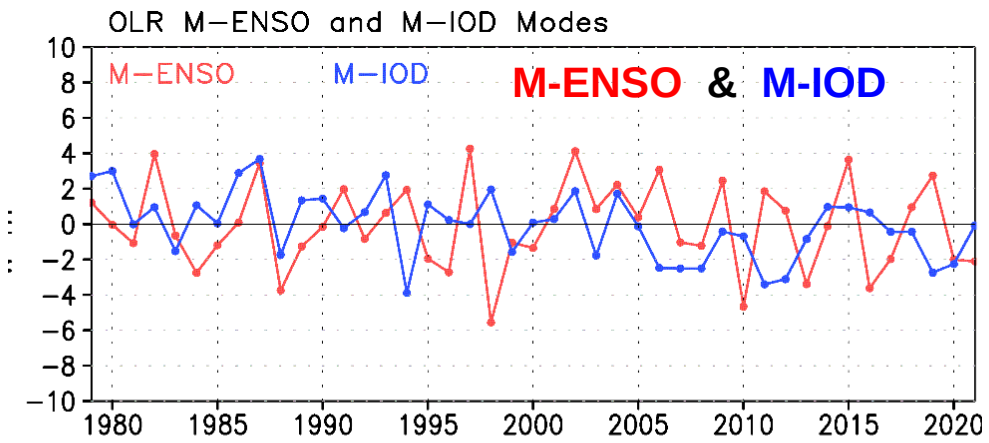
M-ENSO Mode (OLR)

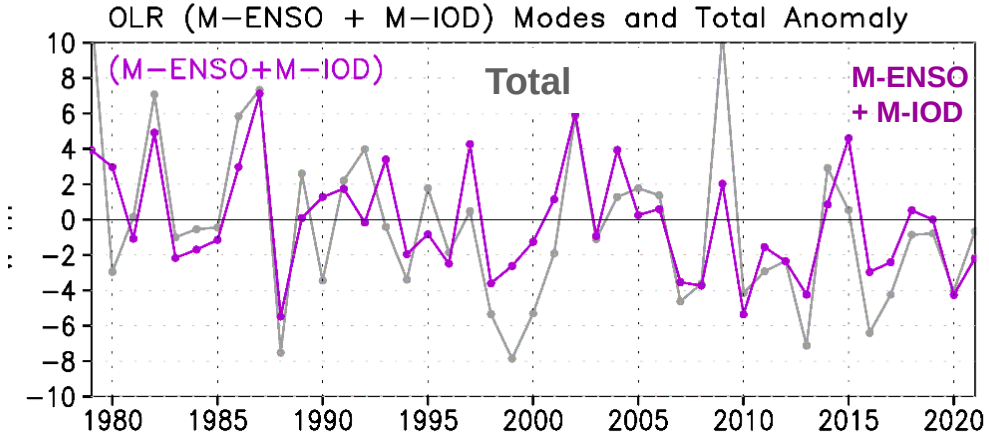


M-IOD Mode (OLR)



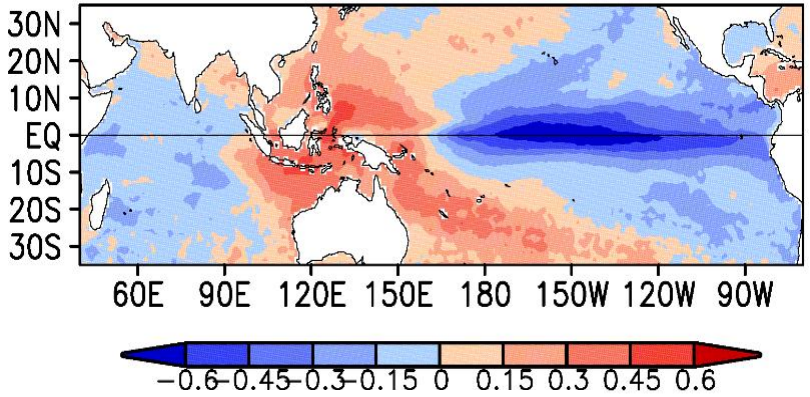
AIM Index of JJAS anomaly



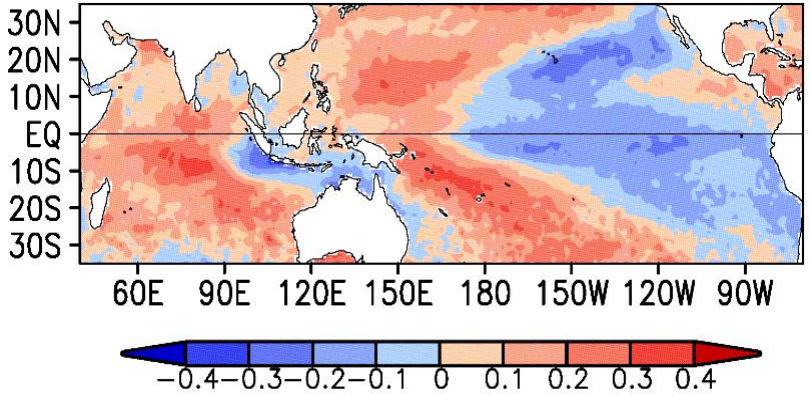


Correlation with daily values of SST and modes

CC: M-ENSO and SST



CC: M-IOD and SST



Seasonally Persisting Modes in OLR

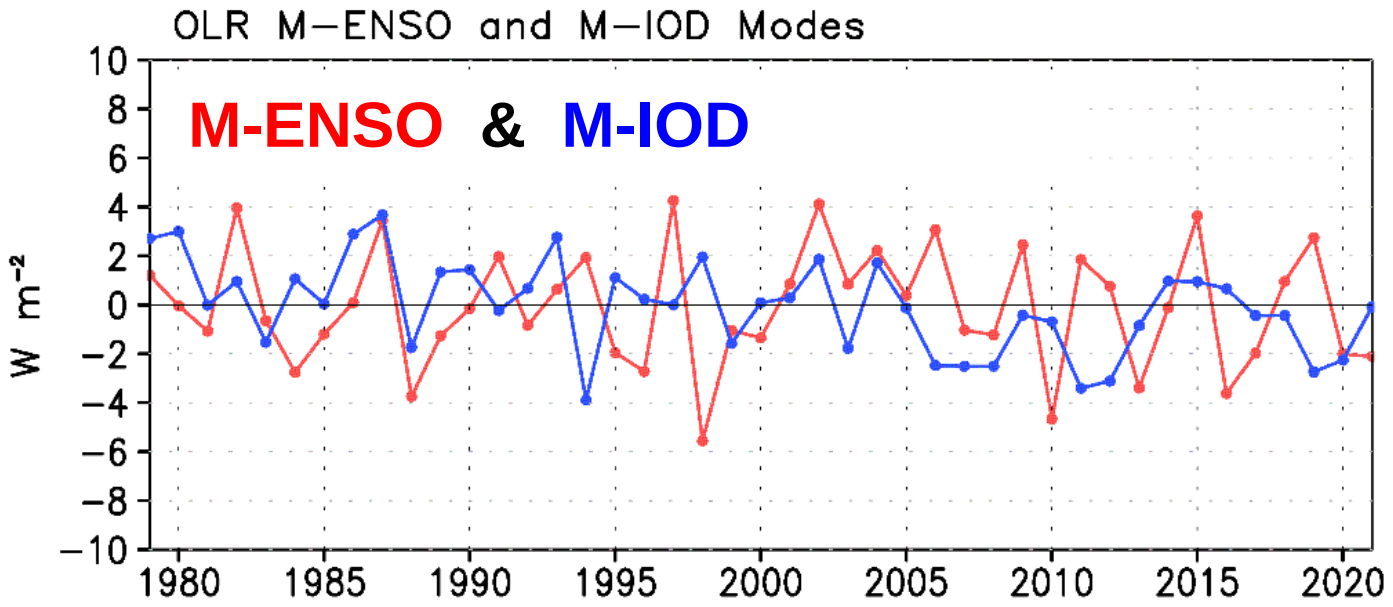
M-ENSO and M-IOD have no phase relationship

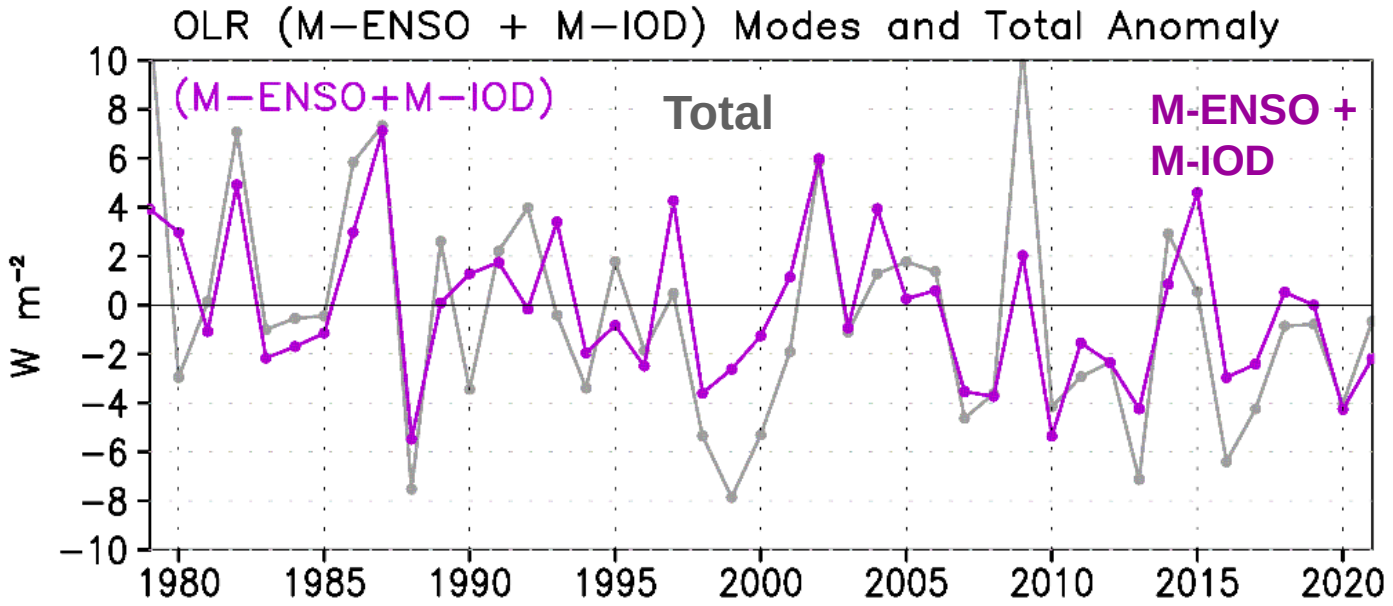
Monsoon-ENSO (M-ENSO) and Monsoon-IOD (M-IOD) modes in OLR

Multichannel singular spectrum analysis (MSSA) of daily OLR anomaly JJAS 1979-2021

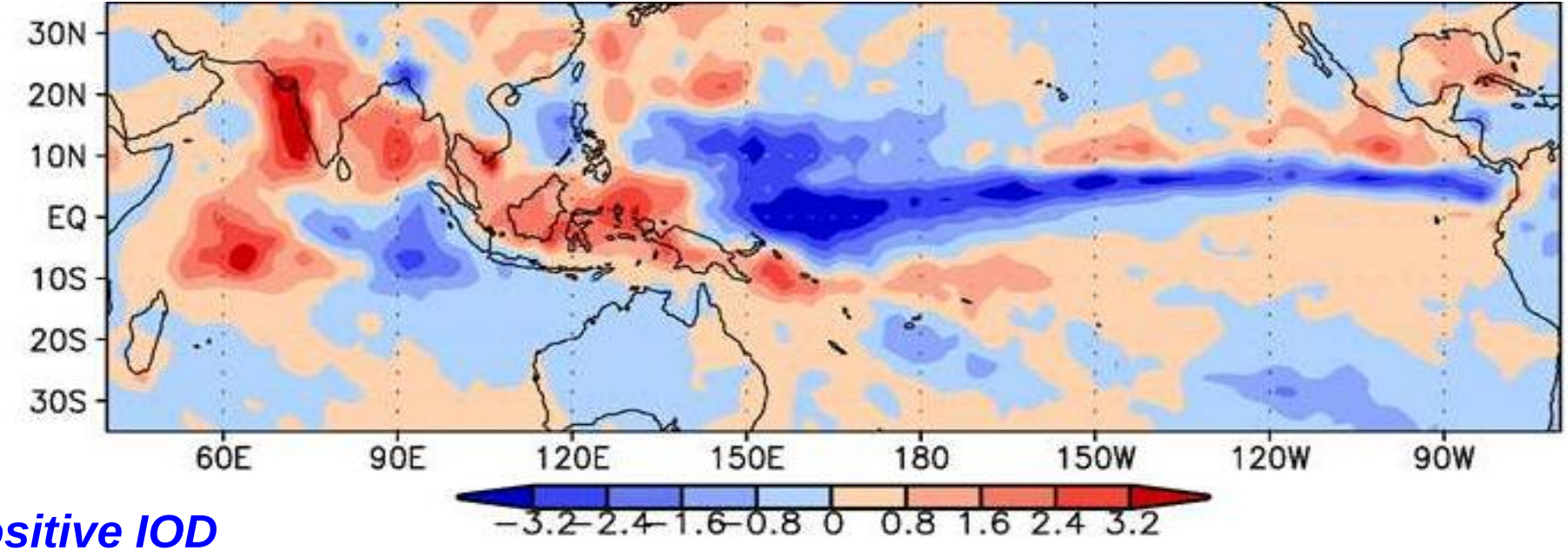
2 seasonally persisting modes: Monsoon-ENSO (M-ENSO) and Monsoon-IOD (M-IOD) modes

M-ENSO + M-IOD have excellent similarity with total OLR Anomaly



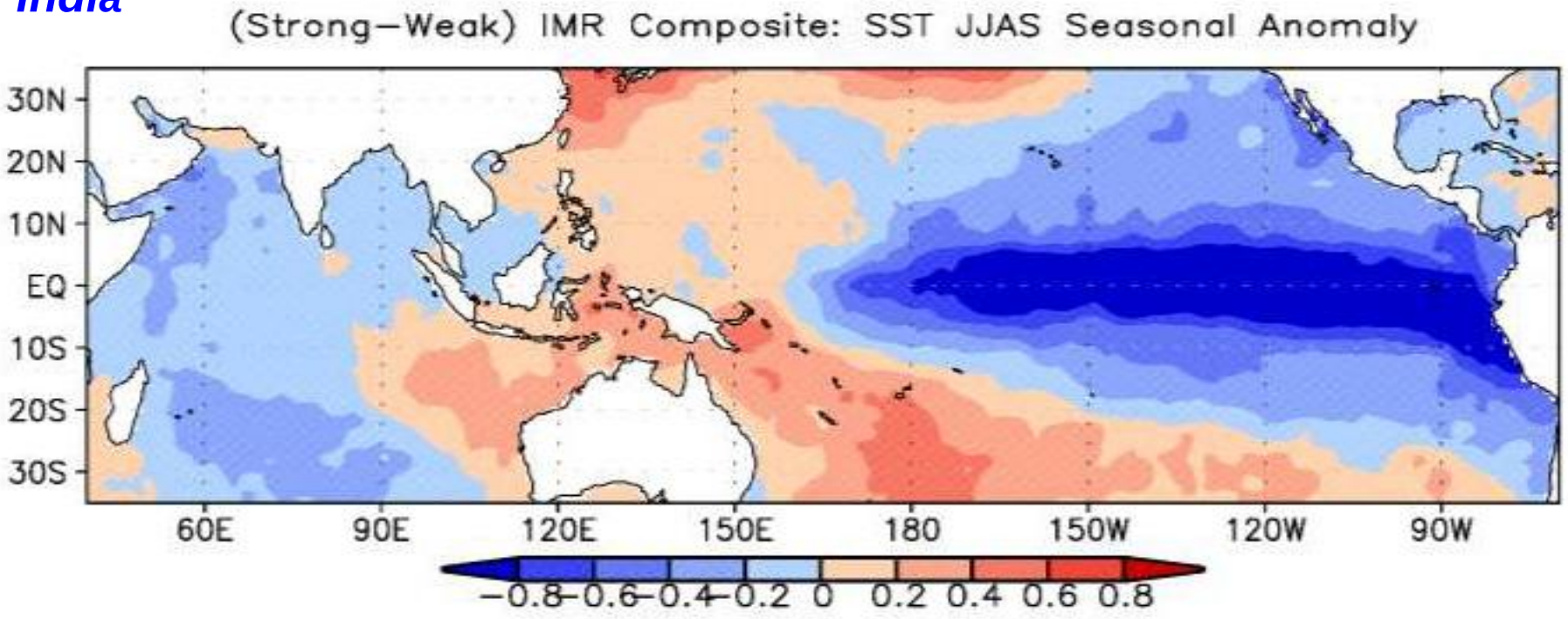


Composite Strong minus Weak JJAS Rainfall Anomaly (CMAP, 1979-2021)



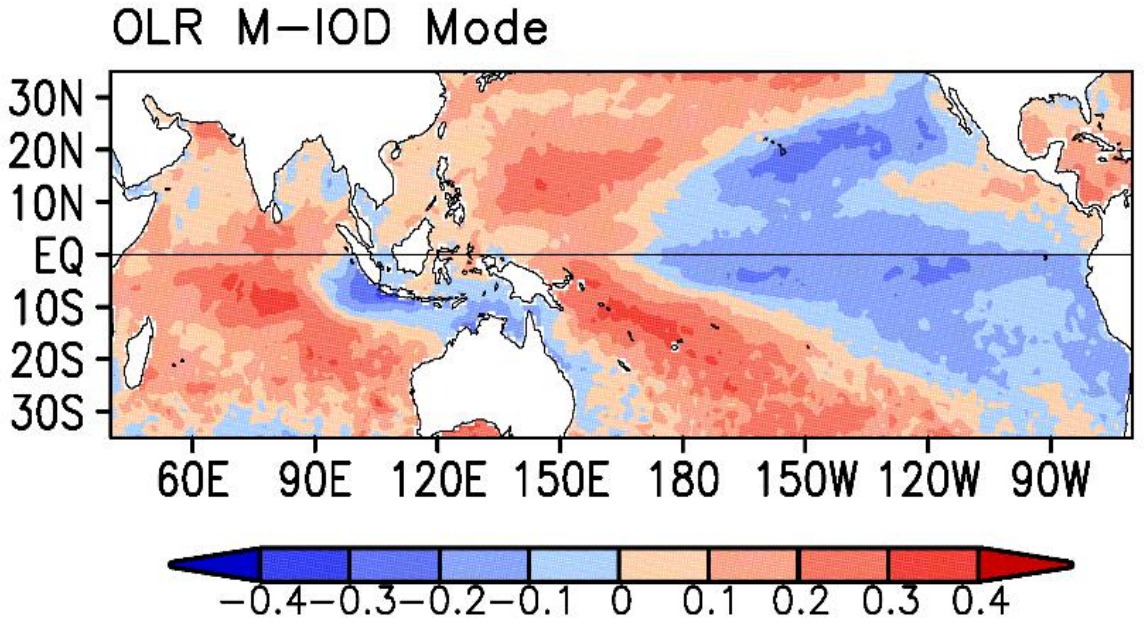
Note: La Nina and Positive IOD give high rainfall over India

Composite Strong minus Weak JJAS SST anomaly (1979-2021)

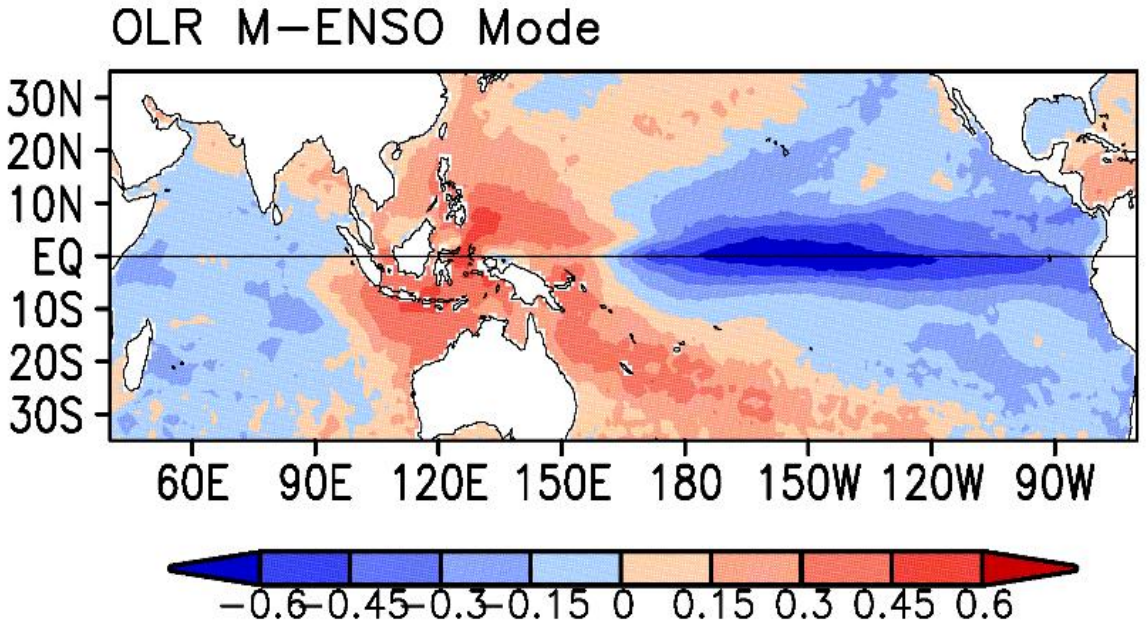


Correlation with Daily SST

Note: Correlations with SST are almost opposite for M-ENSO and M-IOD over the Indian Ocean

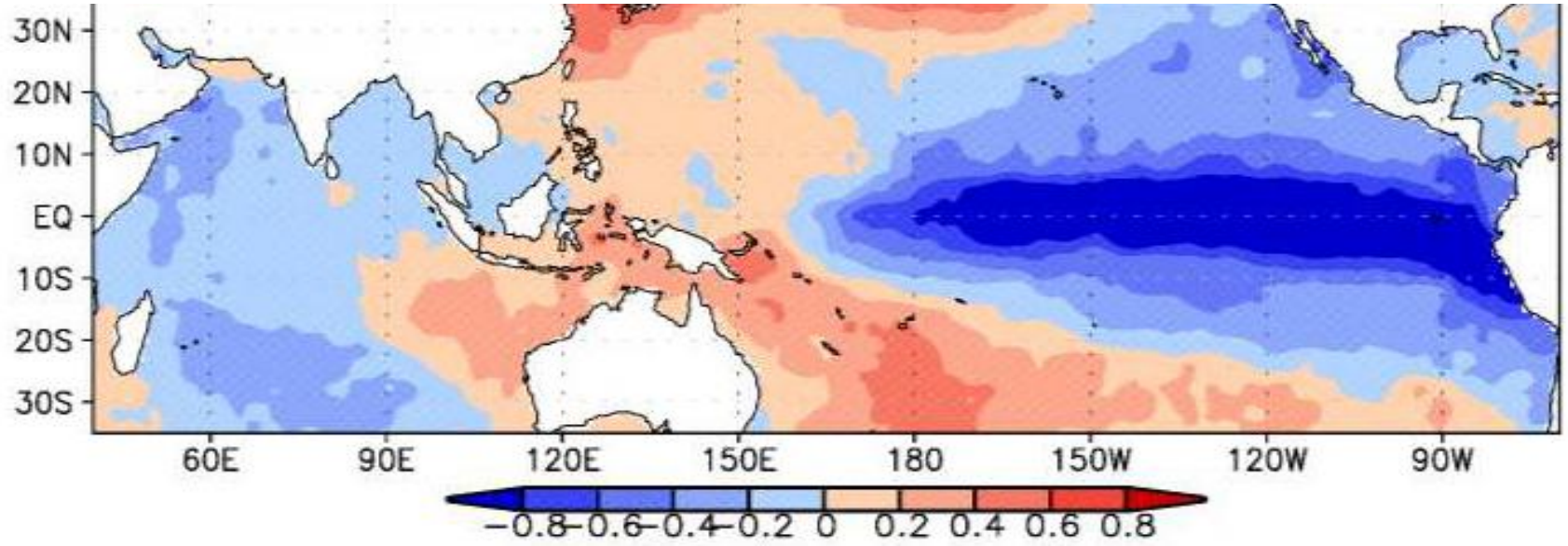


MSSA M-IOD



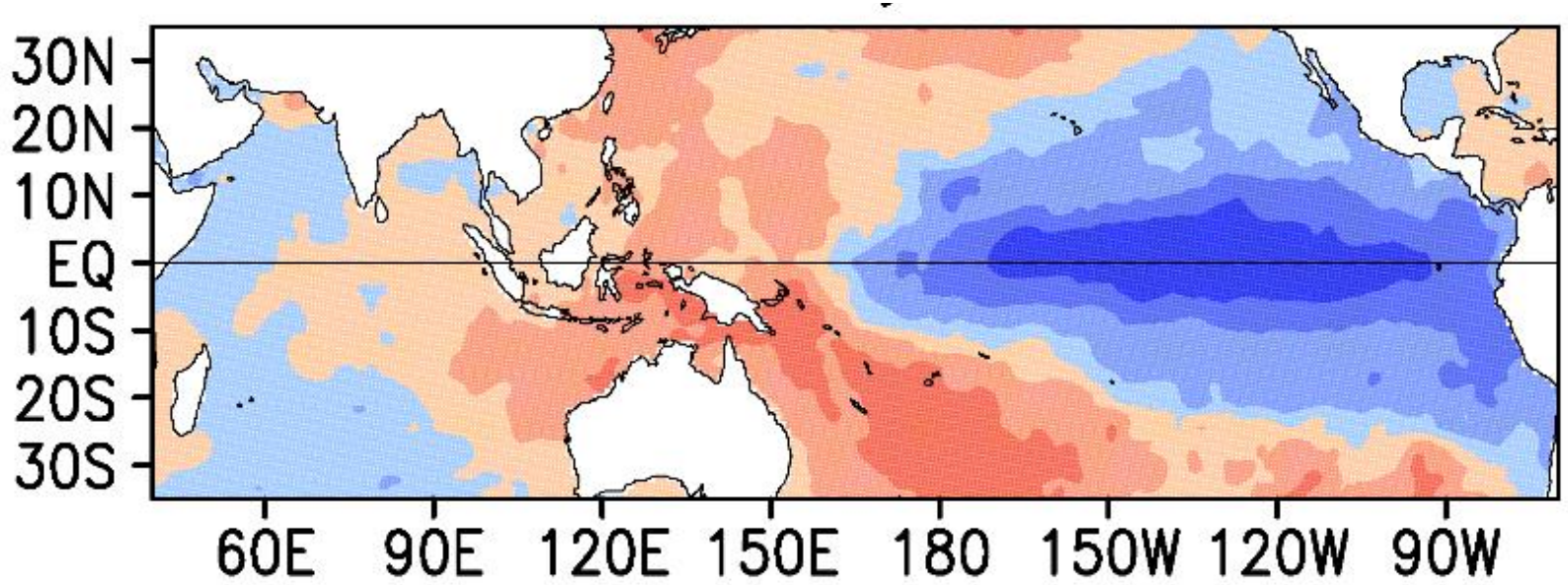
MSSA M-ENSO

Composite Strong minus Weak JJAS SST anomaly(1979-2021)



ENSO-M + IOD-M Rainfall correctly represents correlation with SST

Correlation with JJAS SST for ENSO-M + IOD-M total Rainfall

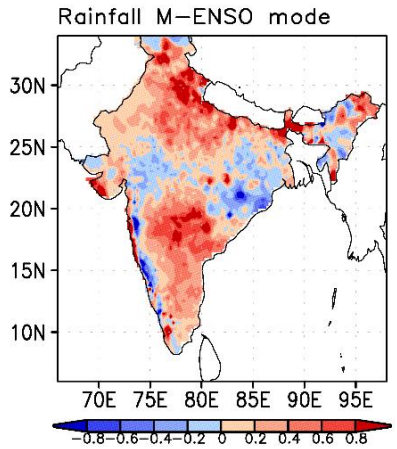


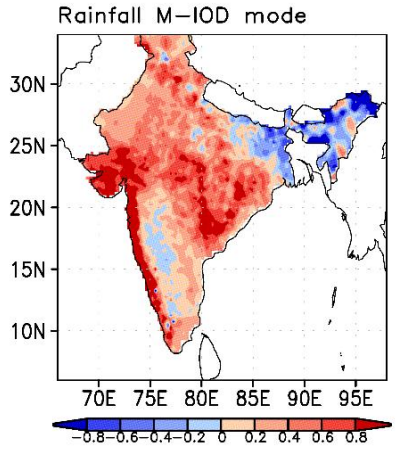
Seasonally Persisting Modes in Rainfall

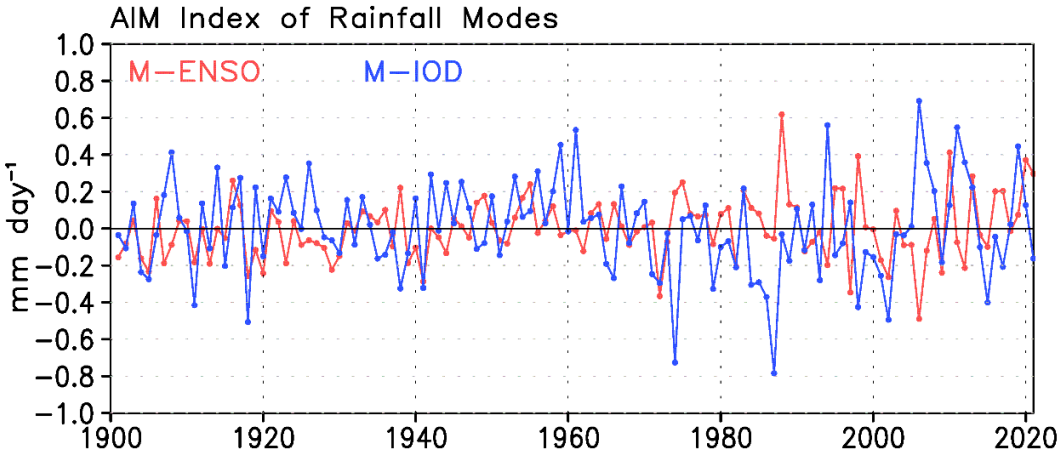
Monsoon-ENSO (M-ENSO) and Monsoon-IOD (M-IOD) modes in rainfall over India

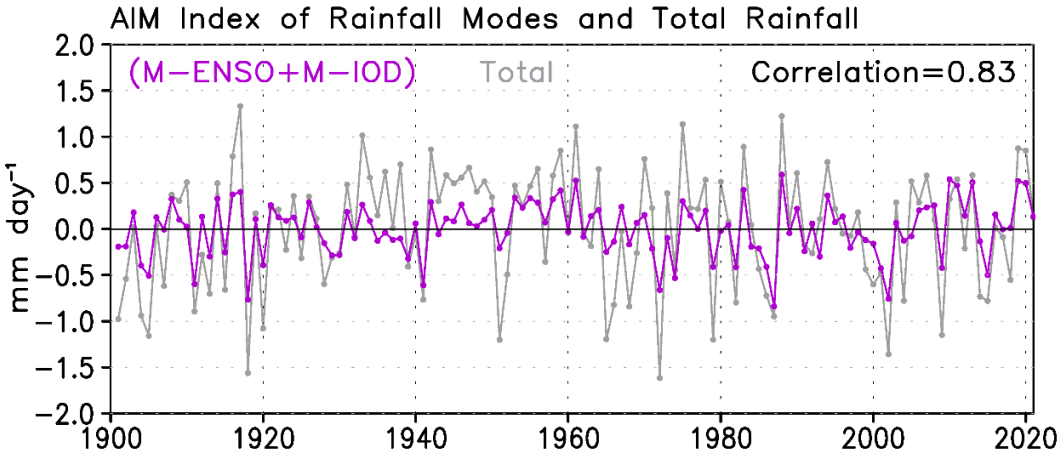
MSSA of daily rainfall anomaly JJAS 1901-2021: 2 seasonally persisting modes: M-ENSO and M-IOD modes

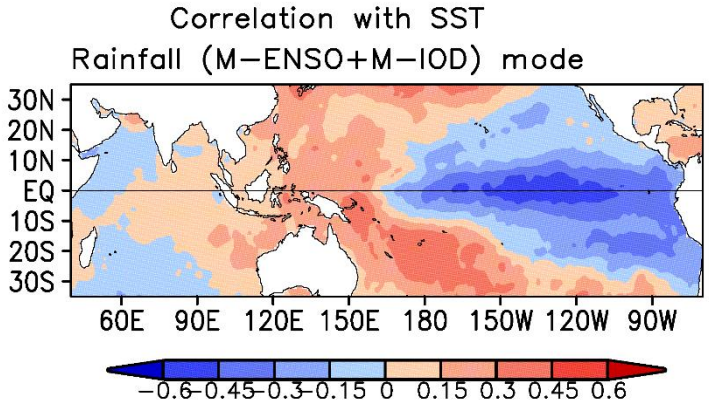
(M-ENSO + M-IOD) modes are correlated with total rainfall with a correlation of 0.83

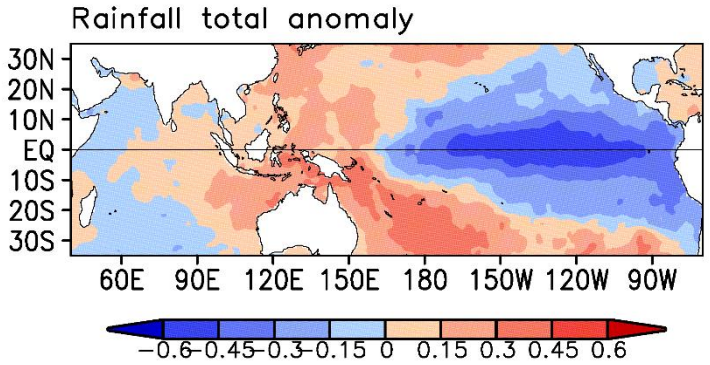




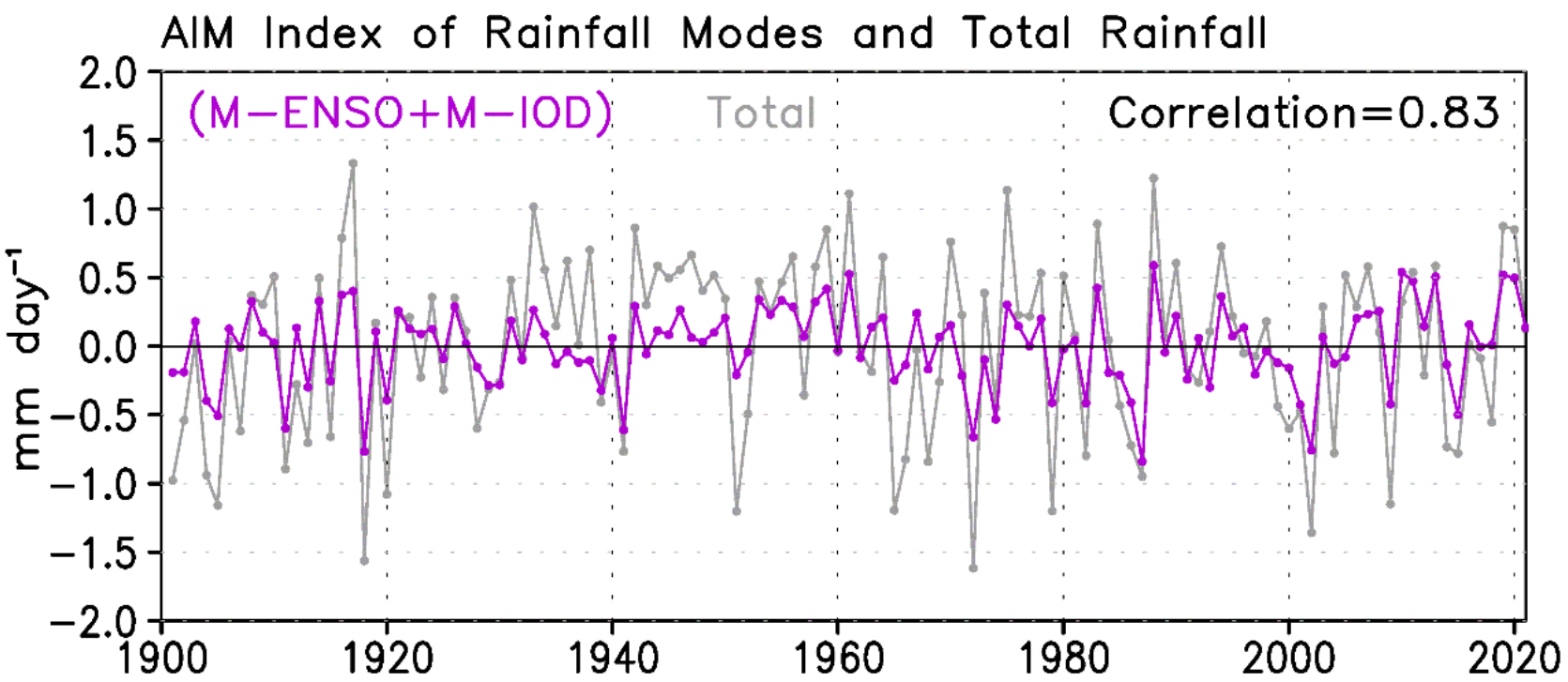






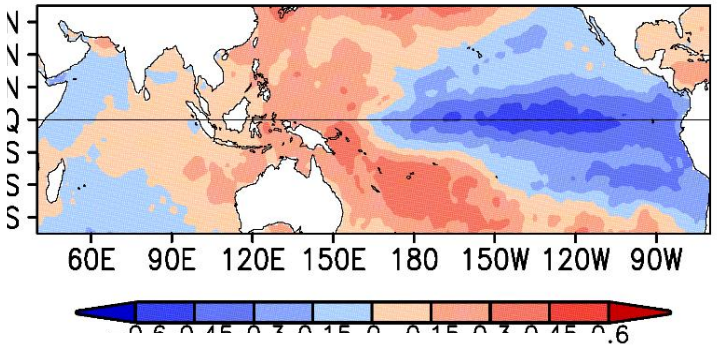


CC between total observed rainfall and sum of rainfall associated with ENSO and IOD modes is: 0.83

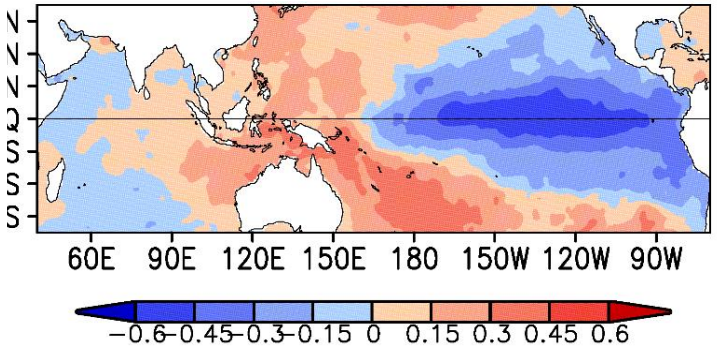


Correlation with SST for:

M-ENSO + M-IOD Rainfall



Observed total Rainfall



It is the combination of ENSO and IOD modes that captures ISMR for 121 years

CC between Rainfall SST is similar for observed rainfall, and ENSO + IOD Rainfall

Epochal Change in Monsoon Rainfall and Ocean Temperature
Note: non liner trends in Rainfall and SST

JJAS 1901-2021
Rainfall over India: AIM index
Pacific Ocean: Niño-3.4 index
Indian Ocean: Dipole Mode Index (DMI)

11-year running mean (black)
Nonlinear trend (red) obtained from
Empirical mode decomposition (EMD)

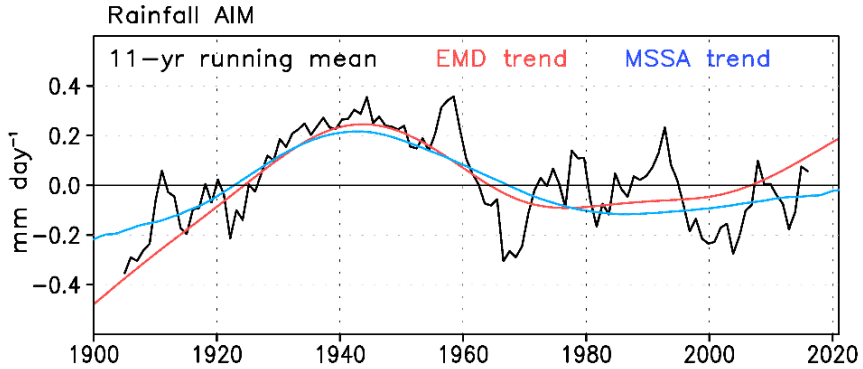
Epochal change around 1960

Epoch 1: 1901-1960
Decreasing or no trend in the Indian and Pacific Oceans
Dominant above-normal rainfall over India

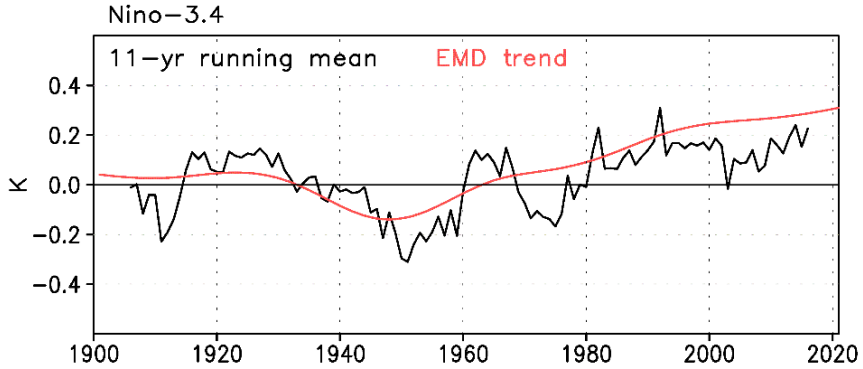
Epoch 2: 1961-2021
Warming trend in the Indian and Pacific Oceans
Below-normal rainfall over India

MSSA of seasonal mean values gives MSSA trend

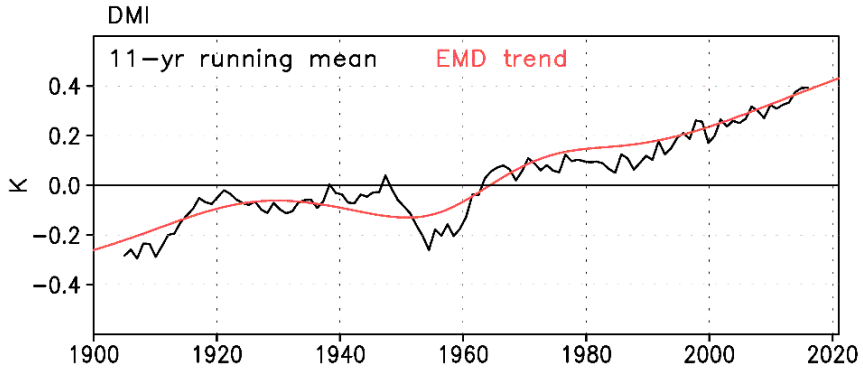
Rainfall AIM



Nino-3.4



DMI



Epochal Change in Monsoon Rainfall

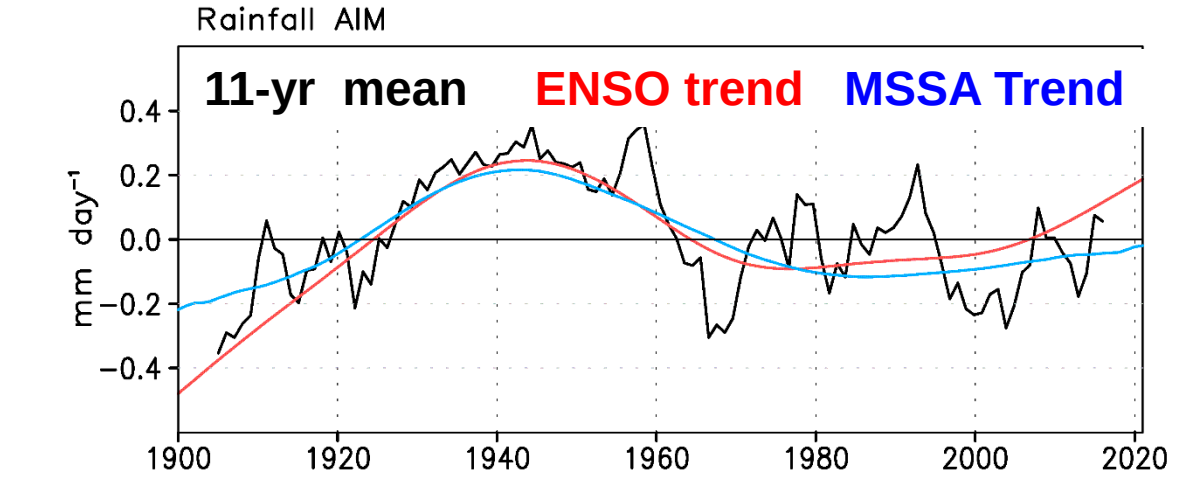
Trends in the seasonally persistent modes

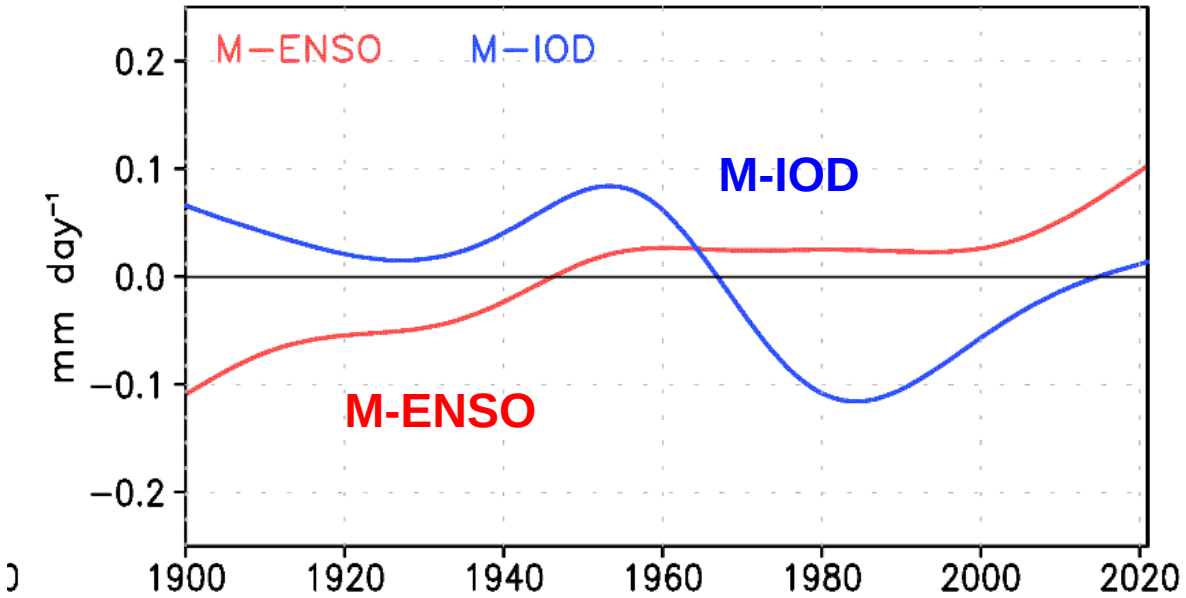
Total rainfall shows nonlinear trend that undergoes epochal change around 1960

Seasonal mean rainfall depends on the relative influences of ENSO and IOD; they can be in phase or out of phase – hence complex relationship between ENSO or IOD and observed rainfall

The M-ENSO and M-IOD modes of rainfall show nonlinear trends that undergo epochal change around 1960.

M-IOD mode has more pronounced nonlinear trend.

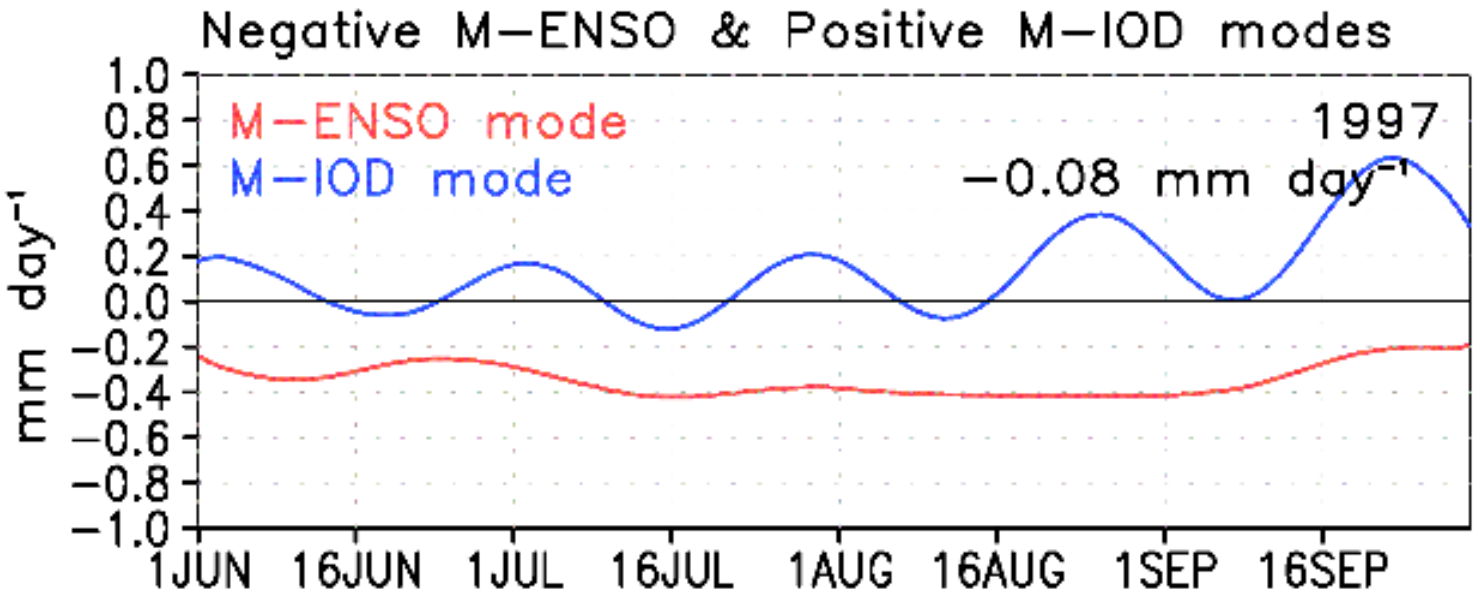




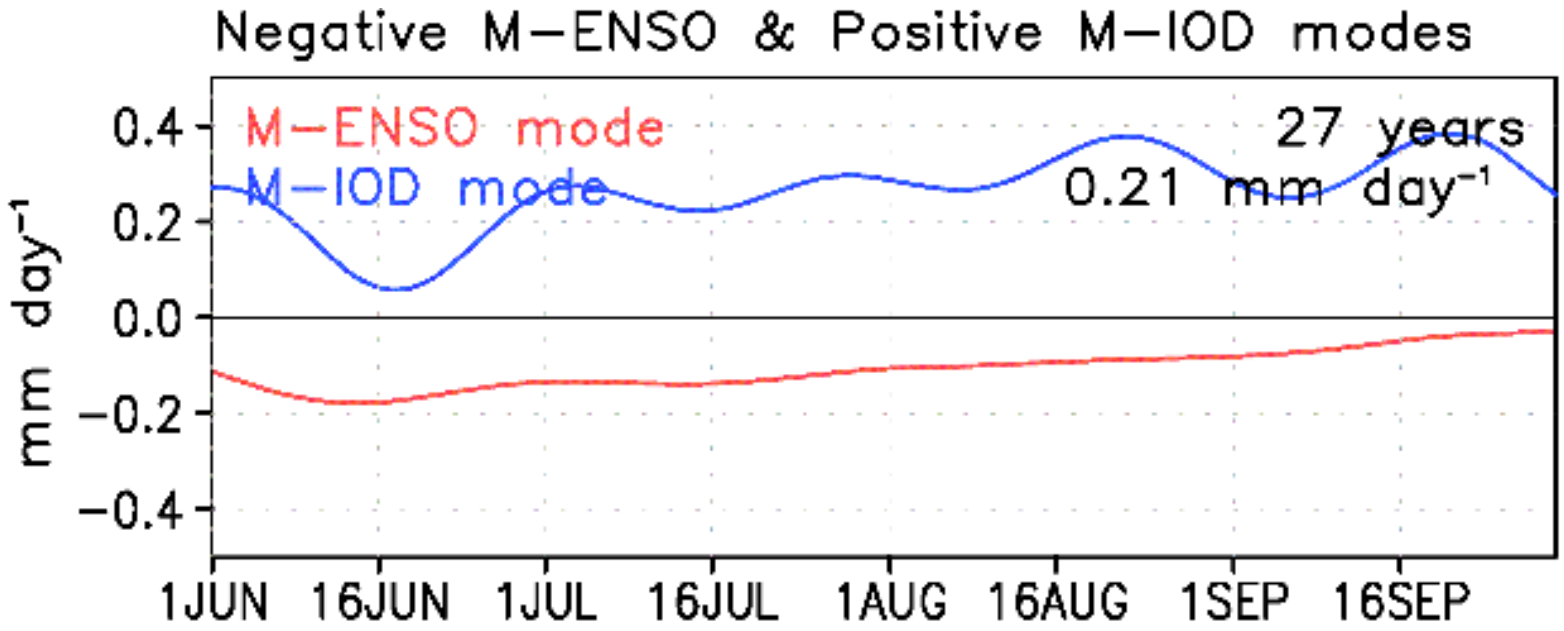
1997: Negative M-ENSO and Positive M-IOD (Normal Year)

Daily variability of AIM rainfall Index for: M-ENSO and M-IOD modes in rainfall

Seasonal mean rainfall depends on the relative influences of ENSO and IOD



1997



Average of 27 years with negative M-ENSO and positive M-IOD

Results of a modelling experiment (not shown)

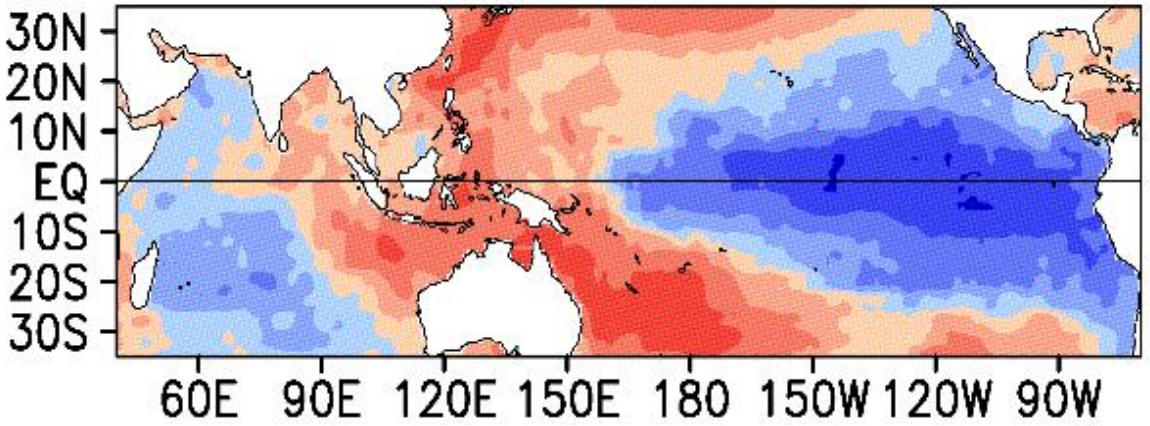
(Chul-Su, Huang, Shukla: 2025, submitted)

- **The CFS forecast for JJAS Rainfall over India for 1997 erroneously produced a major drought, observed rainfall was normal**
- **The major source of error was cooling over western Indian and Arabian Sea**
- **Numerical experiment with observed SST over western Indian and Arabian Sea produced normal rainfall over India as it was observed**

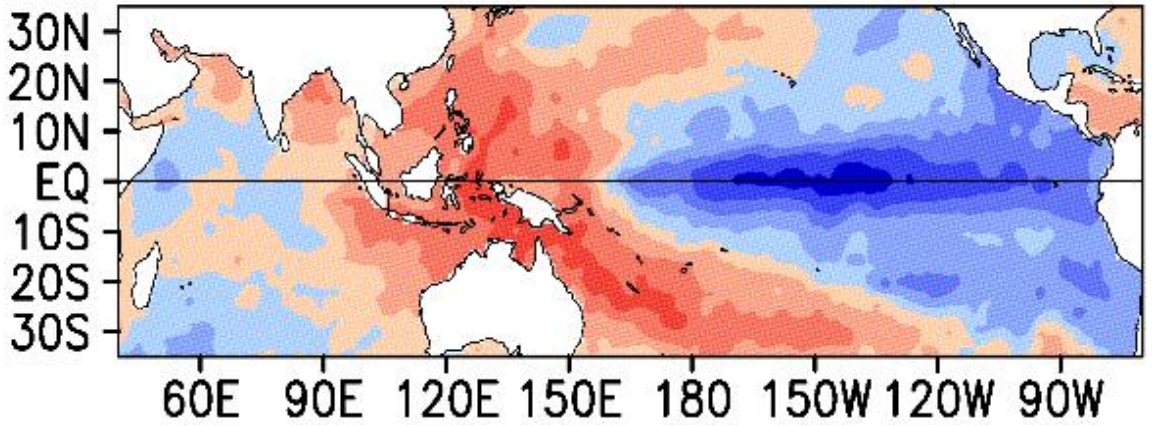
Correlations between SST and ENSO and IOD Rainfall Modes of AIM

Note: IOD Modes are very different in two epochs

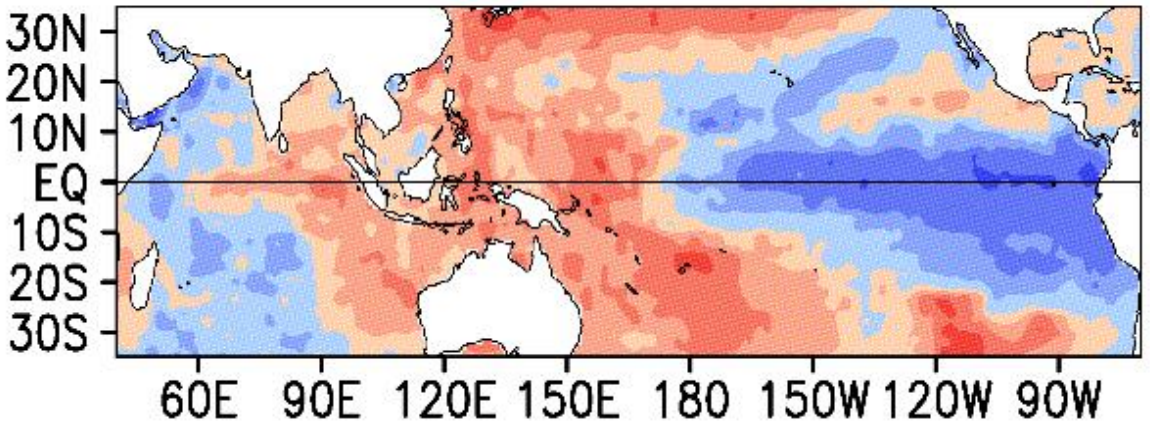
M-ENSO mode: 1901-1960



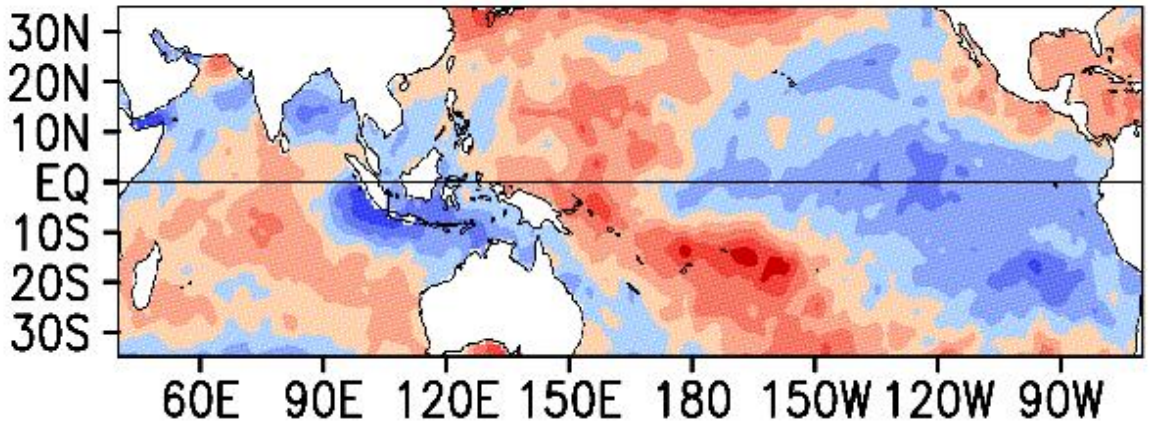
M-ENSO mode: 1961-2021



M-IOD mode: 1901-1960



M-IOD mode: 1961-2021



Epochal change in the relation with SST

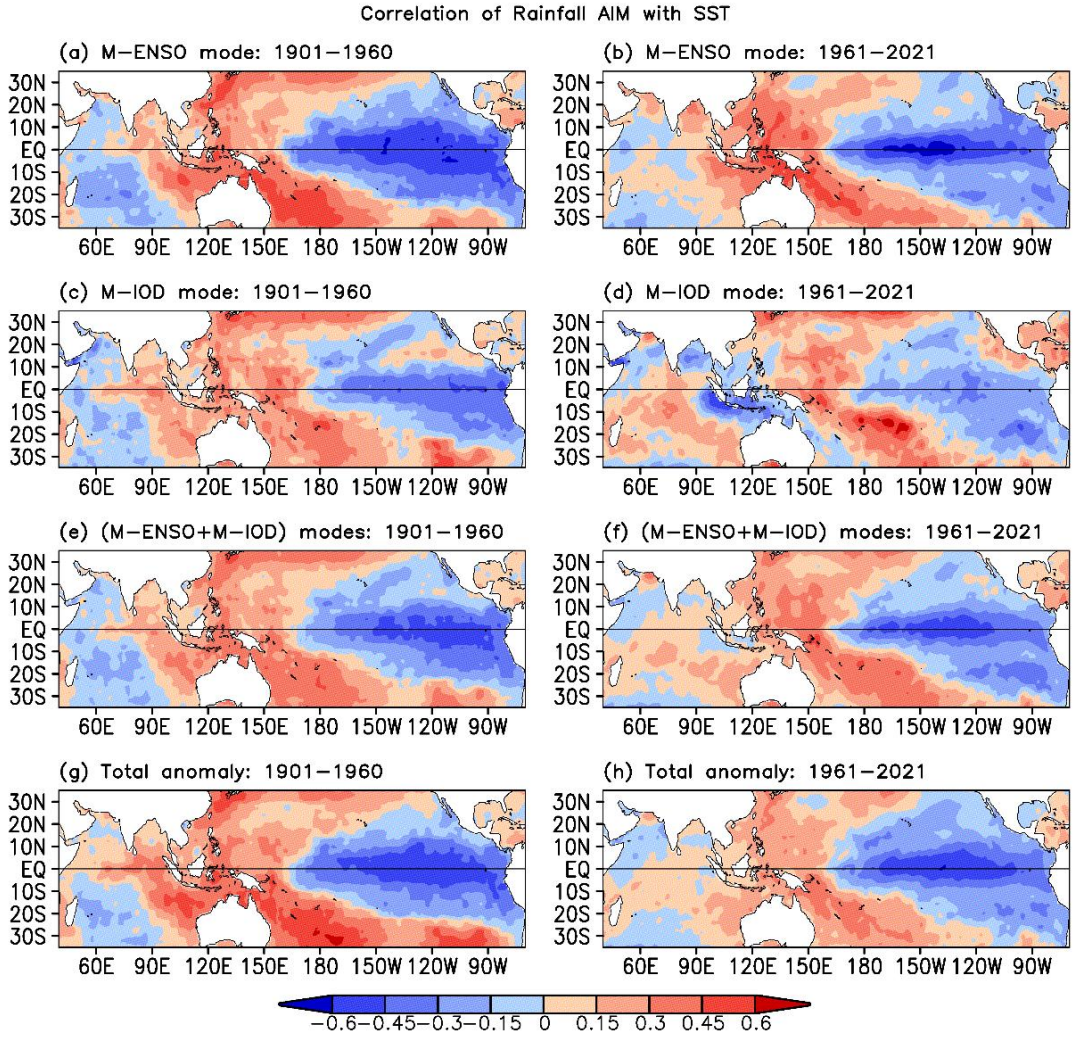
Epoch 1: 1901-1960
Epoch 2: 1961-2021

ENSO-monsoon patterns are somewhat similar In both epochs

IOD-monsoon patterns are different in the two epochs.

Epoch 2 shows a clear dipole pattern with *positive IOD related to above-normal monsoon rainfall and negative IOD related to below-normal) monsoon rainfall*.

M-ENSO + M-IOD modes show good correspondence with total anomaly in both the epochs.



Summary (ENSO, IOD and Epochal changes)

Two seasonally persisting modes related to ENSO and IOD together explain drought and flood years, and inter annual variability (CC:0.83); seasonal rainfall determined by relative strength of ENSO and IOD modes

Relatively rapid warming of the Indian Ocean has changed the relative influences of ENSO and IOD modes which has produced epochal changes in seasonal monsoon rainfall

Accurate and reliable prediction of seasonal mean rainfall over India requires correct prediction of both Pacific and Indian Ocean SSTs, and its influence on rainfall

THANK YOU!

ANY QUESTIONS?